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Phase II: Concept Validation Experiment

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ABSTRACT

This report (Volumes I and II) documents the successful completion of Phase II of the Defense Advanced Research Projects Agency (DARPA) Improving Warfighter Information Intake Under Stress (IWIIUS) program. Volume I discusses the Phase II integration of cognitive state gauges into operational systems that could demonstrate the viability of augmenting cognition into an operational context. Volume II (Appendices) describes the successful results of four industry teams building Closed-Loop Integrated Prototype (CLIP) systems that demonstrate how the limitations of human cognition can be addressed by augmenting cognition with advanced cognitive state sensors that provide input to complex computational systems. A cognitive bottleneck was identified by each of the four development teams along with empirically testable goals. The bottlenecks were operationally defined in terms of the application environments addressed by each of the four teams.

The Honeywell® research team addressed Attention as their primary bottleneck. Attention was operationally defined in the context of a ground infantry soldier in the U.S. Army's Future Force Warrior (FFW) program. The FFW will have more information available (via physical sensors, communications, etc.) and processing that information in a dynamic and lethal environment requires careful management of limited attentional resources. During their Concept Validation Experiment (CVE) they demonstrated a 380% performance improvement where attention resources were required, exceeding the 100% improvement goal set by DARPA. Honeywell® was able to correctly classify attention state changes more than 98% of the time, in less than 300 ms, again exceeding the Phase II operational goals. Finally, they were able to change mitigations in well under the 1-minute deadline established by DARPA as adequate for operational testing.

DaimlerChrysler Corporation (DCC) met all their bottleneck performance goals. They addressed the Sensory Input bottleneck that had significant cognitive impact in the context of a Light Armored Vehicle (LAV) operator. A future LAV operator will have multiple cognitive tasks (e.g., communication, planning, command and control) to manage. Sensory input resources are required by these cognitive tasks as well as by the primary job of maneuvering the vehicle. DCC investigated the sensory bottleneck in the auditory and visual modalities, with multiple mitigation strategies. Their experimental results under real-world driving conditions showed that the sensory bottlenecks could be improved by as much as 108% with an accuracy of up to 98%, depending on the modality being examined. The sensory bottleneck status could be detected in as little as 200 ms, and mitigations could be invoked in as little as 0.2 sec, depending on the mitigation used. The DCC team met all DARPA-defined performance criteria for Phase II of the IWIIUS program.

The Lockheed Martin® Advanced Technology Laboratory (LMATL) addressed Working Memory as their primary bottleneck within the Tactical Tomahawk Weapons Control System (TTWCS) simulation environment. They developed their CLIP for a Tactical Strike Coordinator (TSC), who must manage a number of missiles, targets, and shipboard launch platforms, and dynamically reassign the missiles to targets as critical targets pop-up, missiles fail, etc. The operator must recall and recognize far more information than can be maintained in working memory to perform the task effectively. They demonstrated an improvement in working memory throughput by at least 500% in the context of a U.S. Navy command and control task. LMATL used an Intelligent Sequencing mitigation strategy to strategically present related information about specific missile-target pairings when the Working Memory bottleneck was saturated, achieving a 642% performance improvement, well in excess of the Phase II goal for this bottleneck. Working memory status (high or low load) was correctly identified in over 90% of the trials. The sequencing mitigation took place in less than 500 ms, again meeting all Phase II development objectives demonstrating a successful mitigation for the Working Memory bottleneck.

Finally, the Boeing® team was assigned the Executive Function bottleneck in the context of an Unmanned Air Vehicle (UAV) systems operator. Executive Function is analogous to the central processor in a computer, and relates to the need to process and rapidly assimilate many information elements for a single operator to manage multiple UAVs. Having one operator for multiple vehicles is a pivotal goal for the next-generation U.S. Air Force and Joint Unmanned Combat Air System (JUCAS). Boeing® developed an array of mitigations that were triggered to address the cognitive bottlenecks. With regard to their targeted bottleneck, Executive Function, they empirically showed a 241% performance improvement, with a classification accuracy of 92% in less than 1 second. The mitigations were determined and triggered in less than 1 second as well. Boeing® met all the criteria for Phase II success, not only for the Executive Function bottlenecks, but all four cognitive bottlenecks that were the focus of the program. Table 1 provides a summary of the empirical results for each industry team.

Table 1. IWIIUS Phase II bottleneck results for all development teams.

Team:	Application:	Bottleneck:	Gauge Operational Definition:	Phenomenologic Basis:	Sensor Source(s):	Classification Method:	Mitigation Strategy:	Bottleneck Metric Result:	Classification Accuracy (>90%):	State Detection Time (<2sec):	Mitigation ON (<1min):
Honeywell	**Army: Future Force Warrior (FFW)**	**Attention - Resources**	**Fluctuations in capacity of attentional resources**	**Autonomic nervous system activity, Arousal (PNS from IBI), and Stress (composite gauge expressing SNS activity)**	**IBI, ECG, Pupil, GSR**	**Spectral analysis techniques; linear regression on weighted means**	**Tactile Navigation Cueing (directional cueing)**	**380%**	**98%**	**<300ms**	**<1s**
		Attention - Allocation	**Fluctuations in allocation of attentional resources**	**Relative amplitudes of alpha, beta, and theta waves have been validated as indicators of attention. Switches in attention are modulated by executive function components of the brain. Indicators used in XLI (relative EEG bands between two frontal midline sites at FPz, CPz), Engagement index=beta/(alpha+theta), P300 (evoked potential indicating attention to task relevant stimuli)**	**EEG**	**Spectral analysis techniques**	**Communications Scheduler**	**100%**	**98%**	**<250ms**	**<1s**
		Working Memory	Working memory capacity within multi-tasking environment	Autonomic nervous system activity, Arousal (PNS from IBI); Relative amplitudes of alpha, beta, and theta waves have been validated as indicators of active attention to task execution. Switches in attention are modulated by executive function components of the brain. Indicators used in XLI (relative EEG bands between two frontal midline sites at FPz, CPz); Engagement index=beta/(alpha+theta) at CZ,PZ, P3,P4;	IBI, ECG, EEG	Spectral analysis techniques	Communications Scheduler	155%	90%	250-300 ms	<1s
DCC	**USMC: Light Armored Vehicle (LAV), Marine Expeditionary Family of Fighting Vehicles (MEFFV)**	**Sensory Input (Auditory)**	**Auditory engagement.**	**Power change in alpha band -- individual and task-specific adjustment of sign of change, bandwidth and topographical weights.**	**EEG**	**LDA (Linear Discriminate Analysis)**	**Scheduling**	**108%**	**95%**	**.2s**	**~10s**
		Sensory Input (Visual)	**Visual engagement.**	**Occurrence of demanding driving situations (lane change, overtaking, etc.). Power change in alpha band -- individual and task-specific adjustment of sign of change, bandwidth and topographical weights.**	**Context (vehicle sensors and seat posture) + EEG**	**Context: neural network. EEG: LDA (Linear Discriminate Analysis). All outputs fed to mitigation logic**	**Modality switch**	**72%**	**>95%**	**.5s**	**0.2s**
		Working Memory	Verbal/semantic processing - mental arithmetic.	Power change in alpha band -- individual and task-specific adjustment of sign of change, bandwidth and topographical weights.	EEG	LDA (Linear Discriminate Analysis)	Scheduling	103%	95%	.2s	~10s
LM-ATL	**Tactical Tomahawk – Tactical Strike Coordinator (TSC)**	**Working Memory**	**Verbal and spatial processing can be localized to different areas of brain.**	**Fuse sensors: ICA and other physiological sensors (GSR, EKG) provides general work load, EEG provided localization of verbal/spatial working memory.**	**EEG, Pupilometry, GSR, EKG**	**Neural Net**	**Intelligent Sequencing (through rule based algorithm)**	**642%**	**90.10%**	**.5s**	**5s**
Boeing	**Unmanned Air Vehicle (UAV) Operator**	**Executive Function**	**Shifting context interferes with ability to process information due to need to reaquire all salient information & short-term memory limits**	**Literature suggestes that physiological correlates existed that indicated (measured) cognitive activity**	**EEG/ECG, pupilometry**	**Neural Net**	**Map Declutter Multimodal Cueing Process Queing**	**241%**	**92%**	**1 sec**	**1 sec**
		Working Memory	- Verbal/language processing - Task context	- Increased Activity Localized to Wernike area indicates verbal processing. - Increased pupil area indicates global processing - Task context	fNIR, pupilometry	Statistical Process Control	Sequencing	680%	100% *	1 sec	1 sec
		Sensory Input	- Verbal/language processing - Global processing - Task context	- Increased Activity Localized to Wernike area indicates verbal processing. - Increased pupil area indicates global processing - Task context	fNIR, pupilometry	Statistical Process Control	Process Queing Sequencing Multimodal cueing Map Declutter	283%	100% *	1 sec	1 sec
		Attention	Part-Task Gauge for Tactical Situation Display	Neural Net trained to representative task	EEG/ECG, pupilometry	Neural Net	Multimodal cueing Sequencing	750%	94%	1 sec	1 sec
		Principle Bottlenecks assigned to a development team are denoted by:			**Bold Text**						

EXECUTIVE SUMMARY

Over the last decade many technological advances have been made that affect how rapidly machines collect, store, and share information. Due to this advancement, the information-processing capacity of humans has quickly become a limiting factor in human–computer interactions. This problem has spurred the development of a new scientific discipline called *Augmented Cognition (AugCog)*. Addressing methods for detecting and mitigating limitations of human information processing and designing solutions to enhance exchanging and using information in man–machine systems are the specific concerns of AugCog. The Defense Advanced Projects Agency (DARPA), recognizing the operational implications of this problem for the military, has sponsored the *Improving Warfighter Information Intake under Stress* (IWIIUS) program. IWIIUS is demonstrating how the effectiveness of warfighters can be improved by making the human–computer interface respond to human performance capabilities and limitations in stressful operational environments. In Phase I of the IWIIUS program, the focus was on developing and demonstrating basic component technologies, specifically the development of "cognitive state gauges." This development effort culminated with a Technology Integration Experiment (TIE). The TIE incorporated various sensor technologies and processing algorithms developed during Phase I of the program into a common context that was evaluated simultaneously under the same test conditions, using the same participants. The TIE successfully demonstrated that the technology of detecting cognitive state changes had matured sufficiently to monitor workload in an operationally relevant command-and-control-type decision-making task. The TIE report, issued in 2003, provides an overview of the physiological sensors and algorithms used during Phase I in creating cognitive state gauges to identify, in near real time, an assessment of cognitive state.

This report (Volumes I and II) documents the successful completion of Phase II of the IWIIUS program. The objectives of Phase II, described in detail in this report, built upon the cognitive state gauges created in the first Phase. Phase II extended the work of Phase I by focusing on the development of closed-loop prototype AugCog systems that addressed theoretically derived cognitive bottlenecks that are a limiting factor in human–computer interaction. Each industry team developed the CLIPs, which rely on computational systems to determine the state of the cognitive bottleneck in a warfighter in real time. Whenever the warfighter approached detected cognitive limits (minimum or maximum) of one or more of the cognitive bottlenecks, mitigation strategies were implemented, given the warfighter's current task requirements, to reallocate resources or redirect efforts of the warfighter to enhance overall performance. The mitigations invoked controlled the information provided to and from the operator. Optimizing the warfighter's cognitive state through these mitigation strategies reduces the cognitive bottlenecks to maximize information throughput with the warfighter, and thereby enhances overall human–computer system performance. Four independent industry teams used arrays of physiological and environmental sensors tailored to the operational requirements of four distinct warfighting applications and environments. Each team investigated a different operationally relevant task, specifically addressing one of the cognitive processing bottlenecks identified at the start of Phase II by the DARPA management team. The DARPA management team established performance goals for each cognitive processing bottleneck as criteria for success in Phase II. Table 2 lists each industry team, their military-relevant task area, specific bottlenecks investigated, and transition sponsor. The bottlenecks, metrics, and key technical approaches are identified in Figure 1.

Table 2. Phase II cognitive information-processing challenges.

Industry Team	Military Application	Transition Sponsor	Primary Bottleneck
Honeywell®	Dismounted soldier	Department of the Army	Attention
Daimler Chrysler®	Armored vehicle driver	U.S. Marine Corps	Sensory Input
Lockheed Martin® ATL	Tactical Strike Coordinator (TSC)	ONR	Working Memory
Boeing®	UCAV operator	U.S. Air Force	Executive Function

The ultimate goal of this program is to demonstrate significant operational benefits and consequent military impacts, including (1) enhanced operational effectiveness through specific improvements to warfighter efficiency, (2) an increase in the amount of information that operators can handle, (3) demonstrated ability to reduce manpower requirements (e.g., one person doing the job of two or more), and (4) improving attention management during stressful operations.

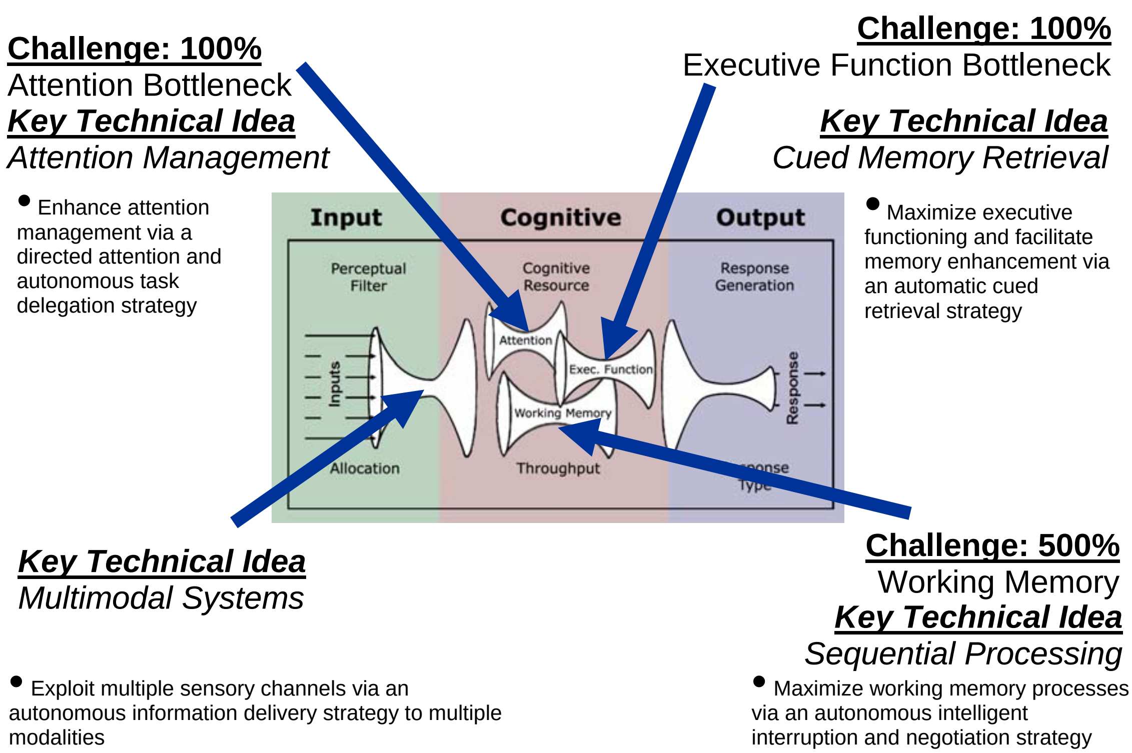

Figure 1. Phase II cognitive bottlenecks and improvement goals.

Each industry team provided a detailed summary (see Section 3) of their accomplishments in defining and mitigating one or more of the cognitive bottlenecks identified for their chosen applications. A brief summary of each team is described below.

U.S. Army—Future Force Warrior (FFW)

The U.S. Army has defined the roles of the 2010-era Future Force Warrior (FFW). The FFW program seeks to push information exchange requirements to the lowest levels and posits that with such enhanced capabilities a squad would cover a battlefield in the same way that a platoon now does. Such tasking requires a full range of netted communications (networked voice and video communications as well as sensor information) and collaborative situational awareness tools to afford the FFW the required information that would afford knowledge of, and coordination between, individual warfighters. Providing improved information processing to the FFW program will enhance the overall capability of small units of forces to complete the complex mission task. These enhancements would reduce the current number of warfighters required to operate in more complex, and less flexible operational units.

Honeywell® Laboratories, selected as the Lead for this effort, conducted task analyses for current dismounted soldier operations and identified several factors that negatively impacted battlefield performance of ground infantry units. One prime factor inhibiting current operations was communication efficiency, a limitation in the ability of individual warfighters to attend to the most crucial communications during critical mission events. Problems in attention have dire consequences in the infantry operational environment. Implications of communication inefficiency include the loss of mission-critical information communicated within and between units. The Honeywell® team examined various methods and procedures to address these problems relating to the Attention bottleneck. This effort specifically addresses one concern of the U.S. Army related to the anticipated increase in information-processing requirements resulting from deployment of netted communications.

The Honeywell® AugCog team consisted of the collaborative efforts of Honeywell® Laboratories, Carnegie Mellon University, City College of New York, Clemson University, Columbia University, Human Bionics, Institute of Human and Machine Cognition, Oregon Health and Sciences University, and UFI. This team developed the Joint Human–Automation AugCog System (JHAAS) for application to the U.S. Army's FFW program. This system exploited real-time neurophysiological and physiological measurements of the human operator to augment the battlefield environment to improve human–computer joint performance. The JHAAS identified specific real-time cognitive state gauges of the human operator's performance for measuring attentional augmentation.

The Honeywell® team adopted an approach that considers the joint human–computer system when identifying bottlenecks to improve system performance. The allocation of attention is critical to FFW because it directly affects two cornerstone technology thrusts of the FFW program: netted communications and collaborative situation awareness. In other words, the appropriate allocation of attentional resources is critical for optimal operator performance. They operationally defined the Attention bottleneck in terms of two aspects of attention defined in prevailing cognitive literature: the cognitive resources that are available within the warfighter at any given time for assimilating information, and how resources are allocated between competing information and processing task demands. Cognitive gauges were developed to monitor information processing that was reflective of two attentional bottlenecks. The gauges developed included electrocardiogram (ECG), electroencephalogram (ECG), galvanic skin response (GSR), heart interbeat interval, and pupil dilation, measures that were validated in Phase I. These measures were integrated through a linear regression of weighted means to identify the operators' cognitive state. The capability to assess cognitive state and determine the

allocation of attention provided the opportunity to evaluate and adapt, if necessary, the soldier's current "interaction" with their task environment. These real-time cognitive assessments could then be used to establish threshold levels to trigger adaptive strategies for mitigating attentional bottlenecks.

Honeywell® investigated how AugCog technologies could be an element of the FFW ensemble and be effective with infantry soldiers. They conducted two Concept Validation Experiments (CVEs) with different sets of experimental questions. One CVE was conducted in a simulation environment and focused on complete sensor integration, development of multiple mitigation strategies to enhance performance, and hardware integration for testing before moving to the field. A second CVE was conducted in a motion-capture virtual environment laboratory to enable data from physiological and neurophysiological sensors to be collected on a physically active individual who moved around the laboratory in a manner more consistent with how a soldier would move in the field. Both environments included tasks that were relevant to the dismounted soldier, including navigating to an objective, identifying friend and foe, eliminating foes, and communicating messages at the squad and platoon level. Mitigation strategies included communications scheduling, tactile navigation cueing system, task offloading with a MEDEVAC (medical evacuation) briefing tool, and an automated target identification assistance tool. Task performance of the individual warfighter was the primary dependent variable when comparing the AugCog condition against performance in an unmitigated baseline condition. The specific dependent measures used to assess performance depended on where the CVE was conducted, and mitigation was used. The central hypothesis of both CVEs conducted was that using mitigations would improve performance without decrementing performance of other concurrent tasks.

Four mitigation strategies were evaluated by the Honeywell® team to address the Attention bottlenecks. The experimental results showed that performance can be improved by 380% for the Attention Resources bottleneck when mitigated with a navigation cueing system, and 100% for the Attention Allocation bottleneck when mitigated through a communications scheduler. The navigational cue system used an innovative tactile belt that signaled the direction they needed to go to reach objective points. The communications scheduling mitigation involved delaying the presentation of critical communications when the system detected high levels of activity in those areas of the brain associated with verbal processing. Other mitigations were also employed to address the Attention and Working Memory bottlenecks, including: offloading procedures and tasks from the warfighter to automation systems, utilizing mixed-initiative automation assistance to recode critical communications to alternative displays (a text display on a handheld computer for instance vice audio-verbal displays on audio communication circuits), and supplementing displays with additional multi-modal cues for time critical communications to highlight objects relating to the critical communications. For example, during high-workload periods, the Communications Scheduler changed the manner in which verbal communication messages were delivered. The Communications Scheduler escalated and highlighted high-priority messages, and deferred low-priority messages by sending them to the tablet PC. By doing this at the appropriate time as determined by sensor gauge outputs, operational metrics improved significantly, 100% improvement in message comprehension and 125% improvement in overall situation awareness. In addition, 85% of participants reported that communication was significantly easier when completing tasks when the mitigations were turned on. The tactile navigation cueing device and the MEDEVAC negotiation tool also significantly enhanced participant performance, as evidenced by 380% improvement in avoiding enemy encounters, no negative effect on ability to identify and eliminate foes, and no negative effect on subjective workload. Eighty-percent of participants reported navigation tasks were easier when mitigation was used. In addition, a 96% improvement in communication of critical information, 303% improvement in time to complete negotiation, and no negative effect on ability to identify or eliminate foes,

with no negative effect on subjective workload. While these performance gains are impressive, the continuous use of these strategies would come at the cost of a loss of situation awareness and survey knowledge of the environment. Such a result highlights the significant contribution of the IWIIUS program by demonstrating the importance of modifying task demands based on a user's cognitive state to enhance performance and that these mitigations must only be triggered when the immediate benefits outweigh the long-term costs to building good situation awareness and survey knowledge of the environment.

The Honeywell® team exceeded the objectives of Phase II by demonstrating that a closed-loop computational system can improve performance in a simulated dismounted-military environment. They showed that when appropriate mitigations were applied at appropriate times, significant improvement in attentional performance was obtained.

Based on post-hoc analyses and comparison with critical events embedded in the test scenarios where high attentional demands were expected, the attentional bottlenecks gauges appeared to accurately reflect high attention demands 98% of the time. The Honeywell® cognitive gauges detected state changes within 250 to 300 ms of the onset of the critical events, and mitigations were invoked within 1 second of the critical event. These improvements are well within the IWIIUS system performance goals established for Phase II. Table 3 provides a summary of the IWIIUS Phase II experimental results for the Honeywell® team.

Table 3. Phase II bottleneck results for the Honeywell® team.

Bottleneck	Gauge Operational Definition	Phenomenological Basis	Sensor Sources	Classification Method	Mitigation Strategy	Bottleneck Metric Result	Classification Accuracy (>90%)	State Detection Time (<2s)	Mitigation ON (< 1min)
Attention – Resources	**Fluctuations in capacity of attentional resources**	**Autonomic nervous system activity, Arousal, and Stress**	**IBI, ECG, Pupil, GSR**	**Spectral analysis techniques; linear regression on weighted means**	**Tactile Navigation Cueing (directional cueing)**	**380%**	**98%**	**<300ms**	**<1s**
Attention – Allocation	Fluctuations in allocation of attentional resources	Relative EEG bands between two frontal midline sites (FPz, CPz), Engagement index = beta / alpha + theta), & P300	EEG	Spectral analysis techniques	Communications Scheduler	100%	98%	<250ms	<1s
Working Memory	Working memory capacity within multi-tasking environment	Autonomic nervous system activity, Arousal (PNS from IBI);	IBI, ECG, EEG	Spectral analysis techniques	Communications Scheduler	155%	90%	250-300 ms	<1s

U.S. Marines—Light Armored Vehicle (LAV)

DaimlerChrysler Corporation (DCC) was selected to participate as an industry team leader for the Marine Light Armored Vehicle (LAV) application. Their status in the IWIIUS program is unique in that they came into the program with a well-defined application and many previously defined mitigation possibilities for augmentation. Their participation in IWIIUS allowed them to explore incorporating cognitive state measures into their previously defined driver augmentation systems, as well as consider augmentation directly targeted at improving human cognition during driving maneuvers. DCC has a long history as leading developers of vehicle and traffic safety systems, as well as innovative vehicle safety systems, making them uniquely qualified to address how augmented cognition might be useful to future fighting vehicles.

The DCC team consisted of researchers and engineers from DaimlerChrysler®, University of Pittsburgh, Fraunhofer Institute FIRST, Sandia National Laboratories, and Transferzentrum für Mikroelektronik. The team concentrated on the integration of an operator sensor suite composed of EEG, a novel seat posture detection system developed in Phase I, ECG, audio monitoring of vehicle occupants, and driver behavior as monitored through vehicle control sensors. DCC collected extensive situational data from the vehicle to assess the driving context in which the secondary cognitive tasks were performed as well as data about the driver's momentary condition in terms of sensory and cognitive processing.

Data acquisition included EEG, participants' verbal responses, reaction times, and recording vehicle-related data via an extended Controller Area Network (CAN-bus) system. Cognitive workload was assessed in real time by two classifiers: (1) two independent EEG-based classifiers trained (neural-network) to detect task-specific neural signal patterns, and (2) a context-based classifier trained to detect potentially demanding driving and traffic situations. For quantifying the AugCog system's success, participant reaction times and response accuracy on the competing tasks were also evaluated and combined to yield an overall operator's performance score. The same data were used to dynamically assess driver stress levels.

Raw gauge and context data were processed into various state gauges through dedicated processing algorithms, and the results broadcast across the vehicle's CAN-bus architecture. The physiological sensor data were processed using a linear discriminant analysis to assess the cognitive state, while vehicle sensor data were processed through a neural network to generate context gauges. The various gauge inputs were then processed through a rule-based system to determine whether augmentation was required, and what mitigation was appropriate to address the two sensory bottlenecks and the Working Memory bottleneck.

Two mitigation strategies were investigated: modality switching, and queuing. Modality switching involved presenting a discrete information-processing task using the visual sensory modality when the cognitive gauges indicated the auditory sensory bottleneck was saturated and there was available visual sensory capacity, or using the auditory channel when the visual channel was at capacity. When both bottlenecks were at capacity, queuing was invoked to delay the presentation of tasks until one of the bottlenecks was available to process information.

The goal of the CVE was to show that despite the continuous high demands on visual sensory input imposed by driving a vehicle, the operator could process significantly more information when it was presented as sensory capacity was made available. To tax the sensory processing associated with auditory sensory input, a second primary navigation task was created in which situational briefs were provided on a continuous basis, with periodic queries regarding previously presented information. Competing secondary tasks required the monitoring of auditory driving directions and mental

arithmetic tasks that created secondary demands on auditory and/or visual processing as well as working memory.

The experimental protocol was carried out twice for each participant (n = 5)—once with and once without the mitigation strategy employed. Tasks were designed to specifically test the Auditory Sensory Input and Visual Sensory Input bottlenecks with the goal of improving throughput of sensory input at least 100%. In addition, DCC elected to address the Working Memory bottleneck to demonstrate an improvement in performance in this environment.

Results indicated that overall operator performance improved significantly on the competing tasks when the closed-loop augmentation system was activated. Without the intervention, competing task performance was significantly lower during periods of high workload. The empirical results demonstrated improvements of 108% for the Sensory–Auditory bottleneck, meeting the IWIIUS program goal for the Sensory bottleneck. DCC also achieved a 72% improvement for the Visual–Sensory bottleneck; this improvement is still highly significant, given that they were using real-world driving tasks on public roads, which are highly demanding for the Visual–Sensory bottleneck, and therefore leave little available capacity for competing visual tasks. The Working Memory bottleneck showed a 103% improvement over baseline (non-mitigated) conditions. Furthermore, driving performance was assessed as the primary task through a number of safety-relevant parameters like distance to vehicle ahead, accelerating and braking events, and steering movements, etc.

The comparison of results for detecting high-demand periods for the sensory bottlenecks and Working Memory from the cognitive state gauges was compared to the context data derived from vehicle dynamics sensors to allow the accuracy and speed of cognitive state detection to be analyzed. The visual sensory bottleneck was accurately detected more than 95% of the time within 0.5 second, and the auditory sensory memory was detected up to 95% of the time within 0.2 second. High periods of working memory load were detected correctly up to 95% of the time within 0.2 second. Mitigations were triggered well under the IWIIUS program goal of less than 1 minute, in as little as 0.l2 second to no more than 10 seconds, depending on the mitigation and trigger event that was called for in the CLIP logic.

The success of the DCC demonstration is expected to serve as the basis for improvement in performing competing mission tasks and dynamic task allocations of military vehicle operators in future demonstrations. The DCC team successfully demonstrated that it is possible to detect cognitive state changes and that this information provides significant improvement in operator performance under closed-loop conditions. Table 4 provides a summary of the IWIIUS Phase II experimental results for the DCC team.

Table 4. Phase II bottleneck results for the DCC team 1.

Bottleneck	Gauge Operational Definition	Phenomenological Basis	Sensor Source(s)	Classification Method	Mitigation Strategy	Bottleneck Metric Result	Classification Accuracy (>90%)	State Detection Time (< 2s)	Mitigation ON (< 1 min)
Sensory Input (Auditory)	**Auditory Engagement**	**Decrease in Power in Alpha Band - localization is task specific - LDA classifier does localization**	**EEG + Context (Vehicle Sensors and Seat Posture)**	**LDA - Linear Discriminate Analysis for EEG and Neural network for Context - sent to mitigation logic**	**1) Modality switch, 2) Scheduling given task requirements**	**108%**	**>95%**	**200ms**	**<1s**
Sensory Input (Visual)	Visual Engagement	Decrease in Power in Alpha Band - localization is task specific - LDA classifier does localization	EEG + Context (Vehicle Sensors and Seat Posture)	LDA - Linear Discriminate Analysis for EEG and Neural network for Context - sent to mitigation logic	1) Modality switch, 2) Scheduling given task requirements	72%	>95%	200ms	<1s
Working Memory	Verbal/Semantic Processing - Mental Arithmetic	Decrease in Power in Alpha Band - localization is task specific - LDA classifier does localization	EEG	LDA - Linear Discriminate Analysis for EEG	Scheduling	103%	>95%	200ms	<1s

The long-range implications of using DCC augmented cognition technology in the LAV environment will be twofold: the workload of the crew could be dynamically allocated between the driver, vehicle commander, and additional vehicle occupants (1) by better sharing of various tasks based on the cognitive state of each crew member and the autonomous capabilities of the vehicle, (2) by using the augmented cognition system to focus the crew's attention on the most critical tasks, and (3) by having the augmented cognition system report on the cognitive status of crewmembers (during over- and under-workload conditions). Furthermore, the driver's ability to safely operate the vehicle would be increased by (1) automating and assisting in driver functions when appropriate, and (2) prioritizing caution and warning indicators through the most effective sensory channel. These applications will be explored as part of Phase III.

U.S. Navy—Tactical Tomahawk Weapons Control System (TTWCS) for the Tactical Strike Coordinator (TSC)

Lockheed Martin® Advanced Technology Laboratory (LMATL) was selected as the industry team lead for the Command and Control environment. They conducted a CVE using a Tactical Tomahawk Weapons Control System (TTWCS) simulation environment. The task environment that was used for the CVE was targeted at the Tactical Strike Coordinator (TSC), a single operator who performs one of the most cognitively demanding jobs in the Navy, and a position that is expected to become more demanding as the TTWCS mission evolves[1]. The TSC must manage missile strikes from multiple platforms against numerous targets in the operational theater. Extremely high cognitive demands are placed on the operator's working memory. The operator must "flip" through multiple display views to collect information needed to make retargeting decisions. This application is a clear choice for assessing the ability to mitigate the Working Memory bottleneck that occurs during

[1] This job is so difficult that it is the one operational billet in the Navy where a new operator must perform a full deployment with his/her predecessor to gain adequate proficiency before being allowed to do the job alone!

the operator's task performance. The LMATL team conducted a cognitive task analysis of the TSC position and concluded that the demands on working memory of the TSC are highly consistent with the Working Memory bottleneck outlined by the DARPA management team. The team was lead by LMATL collaborating with Design Interactive, NovaSol, Anthrotronix, Advanced Brain Monitoring, Drexel University, University of Virginia, and Eyetracking, Inc.

The LMATL team tested a variety of sensor technologies as inputs to developing working memory gauges. Several of the gauge technologies supported during Phase I of this program were used at different stages of development. The final sensor suite included EEG from nine wireless EEG sensors as well as pupillometry data on pupil size for each eye, which served as the basis for a stand-alone Index of Cognitive Activity (ICA) gauge. EKG and GSR were also collected.

Based on a cognitive task analysis of the TSC position and a widely recognized theory of working memory known as multiple-resource theory (Wickens, 1984), the LMATL team operationally defined the Working Memory bottleneck as consisting of two principle channels: visual-spatial information and auditory-verbal information. Their approach was to detect when an operator's cognitive demands were high using the ICA, and then to use EEG to localize what channel was most likely contributing the high working memory demands. Based on this information, an Intelligent Sequencing mitigation strategy was turned on. In this strategy, non-critical alerts were held in a queue during physiologically determined higher workload situations and re-scheduled to occur during lower workload situations. Critical alerts would be presented through that channel that was least heavily loaded.

The LMATL architecture evolved into a system that should prove robust for future development. The final gauge suite used only the raw data feeds from each of the individual sensors rather than independent processors providing derivative "gauge" values, as was seen in IWIIUS Phase I. All gauge values were computed through a Cognitive State Assessor (CSA) that served as an integrated working memory gauge processor. The CSA employed a neural network to generate gauge values for verbal and spatial working memory. These working memory gauge values were then sent to the PACE (Performance Augmentation through Cognitive Enhancement) processor to manage tasks and enable the mitigation strategy, which in the current implementation, consisted of intelligent sequencing.

The LMATL team ran 15 volunteers in a simulated TTWCS task in two separate conditions—once with the mitigation turned on and once while it was off. Results indicate a 642% improvement for the Working Memory bottleneck as measured by successful retargeting performance when the intelligent sequencing mitigation was employed. The neural network successfully classified working memory as high or low over 90% of the time based on the workload periods designed into the simulation. The workload classifications took place in under 0.5 second, and the mitigation was triggered 5 seconds from the time a working memory exceeded threshold. The LMATL development CLIP met all DARPA requirements for successfully addressing the Working Memory bottleneck. Table 5 provides a summary of the Phase II quantitative results for the Lockheed Martin® team.

These results (see Table 5) are operationally relevant to future TTWCS development since the added dimension of retargetable Tomahawk missiles, in addition to the pressure for manning reduction, will dramatically increase the frequency with which TTWCS operators will experience working memory overload. Efforts are currently underway to adapt sensors that require direct contact with the skin to be fitted within a helmet/hat that could be worn by TTWCS operators for an extended period in an operational environment.

Table 5. Phase II bottleneck results for the Lockheed Martin® ATL team.

Bottleneck	Gauge Operational Definition	Phenomenological Basis	Sensor Sources	Classification Method	Mitigation Strategy	Bottleneck Metric Result	Classification Accuracy (>90%)	State Detection Time (<2sec)	Mitigation ON (<1min)
Working Memory	verbal and spatial processing	Fuse sensors: ICA and other physiological sensors (GSR, EKG) provides general work load, EEG provided localization of verbal/spatial working memory.	EEG, GSR, Pupillometry, EKG	Neural Net	Intelligent Sequencing (through rule based algorithm)	642%	90.10%	.5s	5s

U. S. Air Force—Unmanned Air Vehicle Control Workstation

Unmanned Air Vehicles (UAVs) have become highly valued assets in modern military operations. Current UAVs are operated with several operators working as supervisor controllers for a single vehicle. Current operational goals for the next generation of unmanned combat air vehicles call for the ratio of operator to vehicles to reverse, that is, having multiple vehicles that can be operated by a single individual. A single operator managing multiple vehicles must process a very high number of information elements on an ongoing basis, which is why the development team focused on Executive Function as their primary bottleneck.

Due to their extensive background in the operation and development of the UAV control station, Boeing® was selected as the industry leader for a team of researchers exploring the Executive Function bottleneck in the context of the anticipated requirements of next-generation UAVs such as the Joint Unmanned Combat Air System (JUCAS) and its associated Mission Control Station (MCS). The Boeing® team conducted cognitive task analyses of several combat UAV missions and determined that a number of cognitive bottlenecks could be addressed in the context of a Suppression of Enemy Air Defenses (SEAD) mission as the application environment. Their goal was to develop a combat UAV system in which a single vehicle operator would effectively manage multiple combat UAVs simultaneously.

This tasking required that the Boeing® team learn how critical decision information is presented to an operator, allowing them to quickly assimilate new information, integrate this information with previously learned information for a particular UAV, and then determine which UAVs had priority for succeeding task management. While all four of the conceptual bottlenecks identified for study during IWIIUS Phase II are critical to the combat UAV controller, the predominant factor was the strategic processing associated with the Executive Function bottleneck. Although this was their specific objective for Phase II, they attempted to address each DARPA-identified bottleneck (Sensory, Attention, Executive Function, and Working Memory). The UAV application environment is well suited for the manipulation of cognitive taskload. Controlling multiple UAVs is cognitively demanding because it forces the operator to frequently shift context within and between tactical and system health tasks for each vehicle and among all the vehicles. The Boeing® team collaborated with Quasar, EyeTracking, Inc., the Air Force Research Laboratory, and NovaSol, given their experience with EEG, ECG, electrooculograph (EOG), functional near-infrared (fNIR), and pupillometry sensors, and the creation of derivative cognitive gauges.

The system architecture used a publish/subscribe system where sensor data were collected and distributed to other system components as needed. The CSA received raw sensor data from the publish/subscribe system. Cognitive gauge values were then computed and published through the

same system. An Augmentation Manager received the output of the cognitive gauges and combined it with context data that were derived from operator behaviors and a computation of the number of impending critical tasks through a rule-based system within the simulation. The Augmentation Manager turned mitigations on and off based on the joint function of the cognitive gauge output and of the mission context data.

Two different approaches were taken in implementing the real-time cognitive state assessor. The initial approach was based on a neural network that received EEG, ECG, EOG, pupillometry, and fNIR sensor data. The neural network was used to detect Attention and Executive Function bottlenecks and was trained to recognize high and low cognitive taskload for the target prosecution task. The augmentation manager presented mitigations when the artificial neural network indicated that target prosecution taskload was high and the task context assessor indicated that a backlog was developing or that a pop-up/time-critical target had been detected. Mitigations for the Attention bottleneck were designed to provide multi-modal cueing to direct the operator's attention to the highest priority task. Mitigations for the Executive Function bottleneck were designed to help the operator quickly reinstate context for the primary target prosecution task.

A follow-on approach in developing a cognitive state assessor was based on a statistical process control model that in its current implementation received only fNIR and pupillometry sensor data. The expectation was that this approach would make the implementation of alternative mitigations for additional tasks easier in future systems. For IWIIUS Phase II, the statistical process control model was used to detect sensory and Working Memory bottlenecks. The Augmentation Manager presented mitigations when the cognitive gauges indicated that target prosecution and/or vehicle health taskload was high, when pupillometry detected global cognitive workload, and when the task context assessor indicated that a backlog of target prosecution or vehicle health tasks was developing. Mitigations for the Sensory bottleneck were designed to support task prioritization, task interruption management, and multi-modal cueing. Mitigations for the Working Memory bottleneck were designed to support task prioritization, task sequencing, and task interruption management.

The Boeing® team conducted a series of CVEs, refining the bottleneck gauges and mitigation strategies iteratively based on empirical results throughout the development process. A subset of data obtained from the CVEs were used in assessing the bottleneck results reported here. The Boeing® development effort met the performance goals for all the cognitive bottlenecks, including a 241% improvement for their targeted bottleneck of Executive Function. Comparing cognitive state detections for the Executive Function bottleneck to data from the pending tasks indicated that the Executive Function bottleneck was successfully categorized 92% of the time, within 1 second of its changing. Changing the mitigation status was done within 1 second of being called for by the Augmentation Manager. These results were well within the program goals of achieving a 100% improvement in Executive Function, with 90% or better accuracy in less than 2 seconds after a state change, and mitigating in less than 1 minute. Table 6 provides a summary of the Phase II results for the Boeing® team. The performance differences observed between the augmented and non-augmented conditions were statistically and operationally meaningful.

Table 6. Phase II bottleneck results for the Boeing® team.

Bottleneck	Gauge Operational Definition	Phenomenological Basis	Sensor Sources	Classification Method	Mitigation Strategy	Bottleneck Metric Result	Classification Accuracy (>90%)	State Detection Time (<2 s)	Mitigation ON (<1min)
Executive Function	**Shifting context interferes with cognitive processing capacity**	**Literature suggested that physiological correlates existed that indicated (measured) cognitive activity**	**EEG/ECG, pupillometry**	**Neural Net**	**Map Declutter, Multimodal Cueing, and Process Queuing**	**241%**	**92%**	**1 sec**	**1 sec**
Working Memory	- Verbal/language processing - Task context	- Increased Activity Localized to Wernike area indicates verbal processing. - Increased pupil area indicates global processing - Task context	fNIR, pupillometry	Statistical Process Control	Sequencing	680%	100%	1 sec	1 sec
Sensory Input	- Verbal/language processing - Global processing - Task context	- Increased Activity Localized to Wernike area indicates verbal processing. - Increased pupil area indicates global processing - Task context	fNIR, pupillometry	Statistical Process Control	Process Queuing, Sequencing, Multimodal cueing, and Map Declutter	283%	100% *	1 sec	1 sec
Attention	Part-Task Gauge for Tactical Situation Display	Neural Net trained to representative task	EEG/ECG, pupillometry	Neural Net	Multimodal cueing and Sequencing	750%	94%	1 sec	1 sec

Conclusion

Phase II of the IWIIUS program was an unqualified success. All four conceptual bottlenecks identified at the start of Phase II were successfully addressed by one or more of the development teams in four different military application environments. Each team demonstrated the ability to detect high cognitive load within a specific bottleneck by using physiological measures of cognitive state. These measures were then used as a trigger to initiate an appropriate mitigation strategy at the appropriate time, providing significant improvements in operator performance. The magnitude of the performance enhancements varied, depending on the task environment and bottleneck. Performance enhancements well in excess of the DARPA goals established at the start of Phase II were realized. The IWIIUS program continues on track, and teams are primed and ready to extend their efforts from the laboratory to the real operational environment under stress during Phase III of the program.

1. INTRODUCTION

Humans are constrained in the amount of information they can manage. The goal of the DARPA Improving Warfighter Information Intake Under Stress (IWIIUS) program is to develop closed-loop computational systems in which the computer adapts the systems operations based on the systems' ability to detect the cognitive state of individual warfighters. Ultimately, these systems will dramatically improve the human–machine performance of warfighters engaged in demanding decision-making tasks. In the course of executing the IWIIUS program, it is anticipated that the scientific discipline of Augmented Cognition (AugCog) that will be established will become the basis for continued scientific and technology developments. The IWIIUS program will demonstrate significant operational benefits and consequent military impacts, including the following:

- Enhance operational effectiveness through specific improvements to warfighter efficiency
- Increase the amount of information that operators can handle
- Reduce manpower requirements: one person doing the job of three
- Improve attention management during stressful operations

This report (Volumes I and II) describes work performed under Phase II of the IWIIUS program. Phase II focused on integrating cognitive state gauges into operational systems that could demonstrate the viability of augmenting cognition into an operational context, which is discussed in this volume. Volume II (Appendices) of this report describes the efforts of four industry teams who addressed four distinct military decision-making applications. Each of their efforts targeted a specific theoretically derived cognitive bottleneck. Each team was tasked with building a self-contained, real-time, AugCog system that would be tested as a closed-loop integrated prototype (CLIP). Each team's CLIP was evaluated through a series of experimental test protocols to demonstrate compelling improvements in the information throughput with regard to the cognitive bottleneck.

Program Overview. The IWIIUS program is being executed as a multi-phase accelerated development program to allow development progress to be periodically assessed as the program matures and to better manage development risks.

Phase I. Phase I of the program was completed in 2003. It focused on developing and demonstrating basic component technologies, specifically the development of "Cognitive State Gauges." This development effort culminated with a Technical Integration Experiment (TIE), where all the sensor technologies and processing algorithms developed during Phase I were brought together in a common test context and evaluated at the same time, under the same test conditions, with the same participants. The results of the TIE became the basis for the Phase I Final Report (St. John, Kobus, and Morrison, 2003) and the awarding of Phase II funding.

Phase I involved the evaluation of 20 psychophysiological derived measures (cognitive state gauges) that were developed under the AugCog program. These gauges came from 11 different research groups and were developed with a variety of theories and scientific backgrounds. The TIE brought these disparate approaches to assessing cognitive state together to be assessed with a common test protocol using a relatively complex cognitive task derived from the real-world decision-making requirements seen with tactical decision-makers. The gauges used a wide range of sensory technologies and were based on very different, yet sometimes overlapping, theoretical approaches. The sensor technologies included fNIR, continuous and event-related

EEG/ERP, eye tracking and pupil dilation, mouse pressure, body posture, heart rate, and GSR. These technologies measured an array of cognitive states such as vigilance, arousal level, executive load, and perceptual/motor load. Gauges were compared across data collection teams for the evaluation of each gauge and its ability to detect changes in cognitive activity as it was manipulated using the Warship Commander Task (WCT) during the experiment.

Phase I Objectives included the following:

1. Examine the state-of-the-art in theory and technology that had been or could be used to assess human cognitive states.
2. Select the most promising technologies and scientists as the basis for DARPA investment to develop cognitive state gauges, i.e., a suite of one or more physiology-based sensors that could be integrated with a processing algorithm to identify changes that theoretically correlate to changes in psychological state.
3. Assess the maturity of those gauges in detecting cognitive state changes and their potential for application to a real-time system that would adapt to those changes to maximize human performance in man–machine systems that would interest the military.
4. Based on this empirical demonstration that cognitive state gauges were feasible with the state-of-the-art technologies that had been developed, Phase I of the IWIIUS program was successful, and DARPA determined that Phase II should be funded.

Phase II. This report documents the completion of Phase II of the IWIIUS program. The successful conclusion of Phase II was defined as having built a fully integrated system where cognitive state gauges could detect changes, trigger augmentation, and measurably mitigate the overload of one of four conceptual bottlenecks defined based on current cognitive theory. Figure 2 shows the four bottlenecks and the rationale for mitigating them.

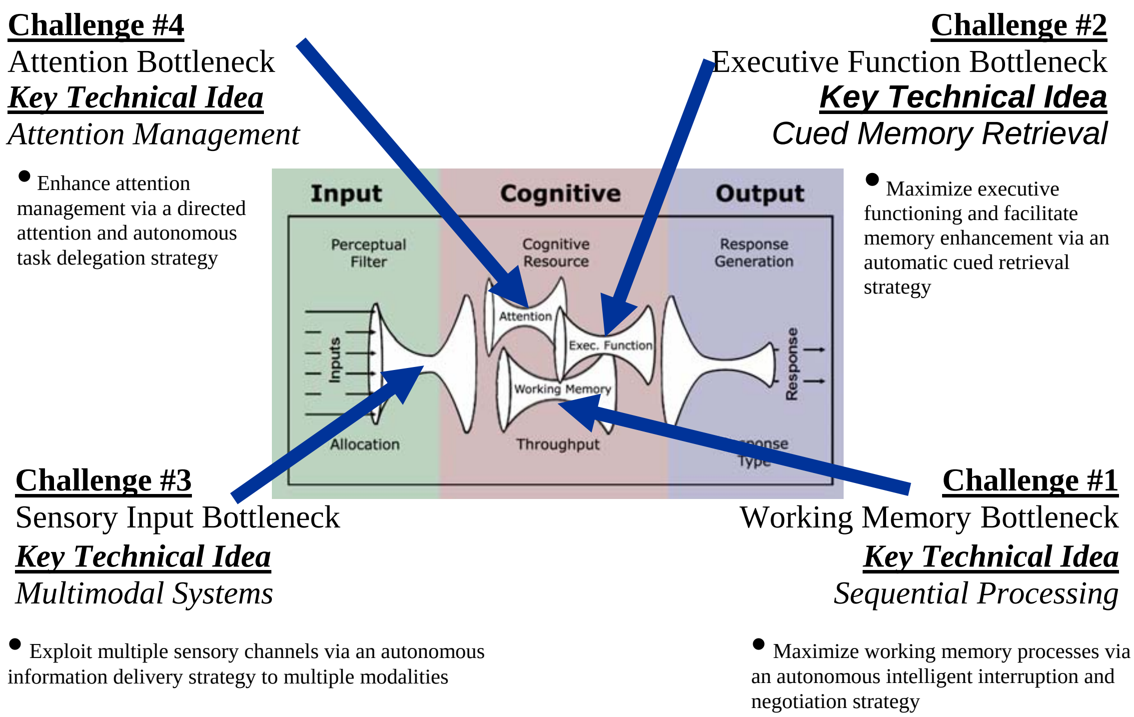

Figure 2. Phase II cognitive information-processing challenges.

Challenge Number 1, the Working Memory bottleneck, refers to the generally accepted theory that human cognition can hold and actively process a limited amount of information. Phase I demonstrated that gauges exist that could detect processing associated with high levels of activity within working memory. Therefore, it would be possible to mitigate this bottleneck by manipulating the order and/or times when tasks requiring significant amounts of working memory were presented to the operator. Tactical command and control tasks such as the Tactical Tomahawk Strike Coordinator require recalling and integrating a large number of information elements in very short time periods. The LMATL team addressed the Working Memory bottleneck in the context of the Tactical Tomahawk Systems Coordinator (TSC).

The Executive Function bottleneck, Challenge Number 2, was derived from the observation that higher order executive control may be involved in moving information from working memory to short-term memory and then onto frontal structures for coordinated decision-making. It was argued that this bottleneck might be effectively addressed through a strategy of cued retrieval, where by facilitating the chunking of related information, and then enhancing the operator's display appropriately during high levels of decision-making, more decisions could be made in short time periods with greater accuracy. UAV operators, who must recall a large amount of highly diverse information for a number of similar vehicles, perform such a task. The Boeing®-led team addressed Executive Function as their primary bottleneck.

The third challenge, the Sensory Input bottleneck, was identified from prevailing cognitive theory. This bottleneck was based on the observation that people can multi-process a significant amount of information when it is presented through different sensory modalities. Therefore, cognitive state gauges could be developed that detect when one or more sensory modalities were saturated, and the presentation of critical information then shifted to an alternate modality. Operating a motor vehicle is a task requiring significant amounts of visual processing, and therefore was an ideal task for demonstrating the effectiveness of mitigating the Sensory Input bottleneck. The DCC team addressed Sensory Input as their primary bottleneck, with an eye toward application in the next-generation, USMC Light Armored Vehicle and the Marine Expeditionary Family of Fighting Vehicles (MEFFVs).

Finally, the Attention bottleneck (Challenge Number 4) was identified based on the recognition that attending to the right information in the first place is a critical part of effective decision-making. Developing interventions that aid a warfighter in attending to the most critical information at any given time could make a significant difference in battle situations. Therefore, the target domain for which the Attention bottleneck was a primary focus was the infantry soldier. The Honeywell®-led team addressed Attention as their primary bottleneck, with an eye toward application to the U.S. Army's FFW program.

Phase II Objectives were defined to include the following:

1. Identify application environments with significant transition potential and a suitable reliance on human operators with significant cognitive overloads so there might be potential for improvement with the introduction of an augmented cognition prototype.
2. Operationally define the cognitive bottlenecks within the context of the chosen application environments, as well as measurable performance metrics on which the bottlenecks could be empirically assessed with and without augmented cognition technologies.
3. Define prospective mitigation strategies that had potential to improve human cognitive abilities based on one or more cognitive state change detection gauges. The strategies identified included the following:
   a. Intelligent interruption to improve limited working memory
   b. Attention management to improve focus during complex tasks
   c. Cued memory retrieval to improve situational awareness and context recovery
   d. Modality switching (i.e., audio, visual) to increase information throughput
4. Develop prototype-augmented cognition systems that would integrate data from various cognitive state gauges that could be used to initiate mitigation strategies to enhance overall task performance.
5. Mature the augmentation prototypes based on the empirical results from a series of CVEs, demonstrating impacts on the identified cognitive bottlenecks and consequent improvements in the overall human–machine performance.

Scientific Underpinnings. Over the last decade, many technological advances have been made in how machines rapidly collect, store, and share information. However, the information-processing capacity of humans has evolved little during this time and has quickly become the limiting factor in human–computer interactions. The AugCog mission is to alleviate cognitive bottlenecks and reduce the human–computer interaction limitations that directly affect military

operations. Cognitive bottlenecks are potential interferences with an operator's ability to process and perform multiple tasks simultaneously. The intrinsic restrictions in the number of mental tasks that a person can execute at one time, and this capacity itself, may fluctuate from moment to moment, depending on a host of factors, including mental fatigue, novelty, boredom, and stress. These limitations include attention, memory, learning, comprehension, visualization abilities, and decision-making.

Working memory applies to a limited-capacity system that can store and manipulate information (Baddeley, 1996). Working memory is significant in military situations because of the limited information capacity and persistence that leads to a cognitive bottleneck, and therefore limited human performance. For instance, overloads in competing tasks could lead to a pilot overlooking the presence of a threat and therefore result in an inappropriate maneuver (Pew and Mavor, 1997). This project intends to maximize working memory processes through autonomous intelligent interruption and negotiation strategy.

Information-processing limitations are often described as processing bottlenecks. The extent of a person's mental capacities and limitations remains a controversial matter (Schumaker et al., 2001). Many researchers are currently testing theories regarding these cognitive mental capacities. For example, a common hypothesis is that a central cognitive decision and response bottleneck (RSB) exists. The RSB is considered the basis for explaining the limited human capacity to process information and is based on the significant body of literature that cites severe and persistent limits found with studies of dual (competing) task performance (Pashler, 1994). The argument is that human processing is essentially serial, and response to a secondary task cannot proceed until after response to the first stimulus has been completed. Additional theories are based on the adaptive executive control (AEC) model for dual-task performance (Meyer and Kieras, 1997a, 1997b, and 1999). The AEC model indicates a declarative knowledge (i.e., verbal descriptions about task requirements) is converted to procedural knowledge (Anderson, 1982; Bovair and Kieras, 1991). Once the information is converted, two tasks may be performed simultaneously in parallel by a notional central processor, and thus the limiting factor in processing is in the sensory input processing, vice executive processing per se.

Wickens (1984) offered yet another hypothesis regarding the serial versus parallel nature of processing by noting that there appeared to be a pattern across the literature suggesting that there were two primary channels of processing: audio-verbal and visual-spatial. Cognitive processing that was verbal and presented through the auditory modality tended to be processed in parallel to information that was spatial in nature and presented visually. Thus, in effect, two relatively independent channels for information processing exist. Only when information supporting two different tasks was presented in the same channel at the same time is interference significant.

The notion of a Sensory Input bottleneck refers to the sensing and perceiving of information that transforms energy into internal representations that can be acted upon by cognitive processes. Potential Sensory Input bottlenecks can interfere with an individual's ability to detect, identify, and properly classify targets for situation awareness (Pew and Mavor, 1997). These types of interferences are a main concern to an operator monitoring visual displays such as radar, sonar, and air traffic control. The current objective is to exploit multiple sensory channels via an autonomous information delivery strategy to multiple modalities.

Finally, attention has a long standing interest in psychology. One long standing theory of attention argues that perception is actively filtered by cognitive processes, and therefore attention can be directed. The ability to attend to specific information may be a skill

that can be trained, or may be facilitated by incorporating distinctive features that allow priority information to be more readily detected.

Physiological Monitoring of Cognitive Activity. The technologies developed over the last decade in measuring brain activity and various facets of cognition are the foundation for the development of augmented cognition. Techniques like functional magnetic resonance imaging (fMRI) have given scientists the opportunity to identify three-dimensional regions of human brain activity during specific mental tasks. This opportunity opened up the field of cognitive psychology substantially (into the new field of cognitive neuroscience) and enabled researchers to test their theories of the human and associate previously observed human behaviors with neural activity in specific brain regions. For example, Jiang (2003) found significant behavioral interference when participants must perform two tasks overlapping in time using fMRI as a metric. The duration of response to both tasks is dramatically increased. The physiological measures used during Phase II of the program will dynamically identify these types of changes in human cognitive activity as warfighters are engaged in cognitive tasks.

2. TRANSITION AREA REPORT

2.1 U.S. ARMY—FUTURE FORCE WARRIOR (FFW) (DISMOUNTED INFANTRY)

2.1.1 Concept Validation Experiment (CVE) Analysis Report Summary

Table 7. Honeywell® Executive Summary of approach and results.

<table>
<tr><td colspan="3">Concept Development and Analysis Team Prime: Honeywell® Laboratories</td></tr>
<tr><td colspan="3">Application: Future Force Warrior (FFW)</td></tr>
<tr><td colspan="3">Hard Problems:
• Soldiers are faced with highly dynamic task environments, many sources of information, unpredictable/variable delivery times—information priorities change as context changes
• With the advent of the Future Force Warrior, the task environment demands will increase further due to netted communications moving real-time information to lower echelons of command
• Two aspects of attention are particularly salient to the FFW: capacity and allocation
• Cognitive research indicates attention is a limited resource that has a fluctuating capacity—available resources are allocated through active cognitive processing.
• Successfully augmenting Attention bottlenecks requires gauges that measure attention resource capacity and attention allocation of the available resources
• The rigorous demands of FFW require sensors and digital signal-processing technology adapted to size, weight, power, ease of use, and durability for the soldier in the field</td></tr>
<tr><td colspan="3">Transition:
• Target Program: Future Force Warrior Program; Cynthia Blackwell Human Performance Lead, Technology Program Office, insert technology by Sept 2007 for Land Warrior Block Upgrade III
• FFW technology demonstration has identified system criteria where there must be sufficient increase in survivability/lethality to justify increase in additional size, weight, power, cost, and complexity of FFW systems</td></tr>
<tr><td colspan="3">Test Conditions:</td></tr>
<tr><td>Scenario</td><td colspan="2">IHMC
• Simulation-based (participants seated) Military Operations on Urban Terrain (MOUT) addresses Attention bottlenecks
• Scenario—Navigate to objective
o SA where they are, where enemy is, where they need to go
o Manage communications
o Avoid ambushes
o Engage enemy
o Complete MEDEVAC
CMU
• Virtual Reality (VR) Simulation (upright and mobile) MOUT addresses Working Memory bottleneck and sensor stability issues with physically active participants
• Scenario—Situational Awareness
o Identify friend/foe
o Engage enemy
• Manage communications</td></tr>
<tr><td>Participants</td><td>IHMC
• N = 13
• University students and staff</td><td>CMU
• n = 10
• University students</td></tr>
</table>

Table 7. Honeywell® Executive Summary of approach and results. (cont)

<table>
<tr><td rowspan="6">Gauges</td><td>Gauge and Developer:</td><td>Tested</td><td>Used</td></tr>
<tr><td>Engagement Index—NASA/Honeywell®/CCNY</td><td>✓</td><td>✓</td></tr>
<tr><td>Cognitive Workload (Stress)—Institute of Human Machine & Cognition</td><td>✓</td><td>✓</td></tr>
<tr><td>Arousal Meter—Clemson University</td><td>✓</td><td>✓</td></tr>
<tr><td>eXecutive Load Index—Human Bionics</td><td>✓</td><td>✓</td></tr>
<tr><td>P300 Novelty Detector—City College of New York/Columbia</td><td>✓</td><td>✓</td></tr>
<tr><td>Integration Architecture</td><td colspan="3">• Sensor (EEG, IBI, HFQRS ECG, Pupillometry, GSR, Pleth) output through network to agent-based architecture
• Sensor data subjected to different analysis to support different gauge(s)
• For attention resource gauges (sensors IBI, ECG, Pupil, GSR) spectral analysis and linear regression on weighted means to values for Stress and Arousal gauges
• For attention allocation gauges (sensor EEG) spectral analysis is used to create a XLI, P300, Engagement gauge values
• Output of gauges feeds rule-based cognitive state profiler through agent-based architecture
• Cognitive state profiler determines 1) attention resources capacity 2) appropriate allocation of attention resources to process information</td></tr>
<tr><td>Mitigation Rationale</td><td colspan="3">• Multiple mitigation strategies were explored across CVEs.
• Mitigation strategies were context dependent and included
  o IHMC: communications scheduler, tactile cueing, MEDEVAC agent, mixed initiative target id
  o CMU: communications scheduler
• Cognitive state defined by rule sets using different sets of gauges
  o IHMC: Any single gauge triggered the mitigation
  o CMU: At least 2 of 3 gauges needed to reflect high workload or rate of change toward high workload state
• Communications Scheduler
  o IHMC: Scheduled and presented messages based on the cognitive state profile, the message priority, and current context
  o CMU: rescheduled communications during high workload states
• Tactile Navigation Cueing
  o 24-element tactor belt (15º resolution) provided pulse in desired navigation direction – frequency indicated proximity
  o Turned on when attentional resources were limited, once triggered stayed on for duration of navigation task
• MEDEVAC Agent – Executed medical evacuation of casualties with minimal information. Agent triggered when attentional resources were limited.</td></tr>
<tr><td>Experimental Design</td><td colspan="3">• IHMC: Single factor (mitigation on/off) repeated measures
• CMU: Single factor (mitigation on/off) repeated measures</td></tr>
<tr><td>Independent Variables</td><td colspan="3">• IHMC: Mitigation (none, augmented)
• CMU: Mitigation (none., augmented)</td></tr>
<tr><td>Dependent Variables</td><td colspan="3">• IHMC
  o Percentage change in number of ambushes avoided served as measure of attention resource capacity
  o Percentage of messages comprehended served as measure of attention allocation
• CMU
  o Percentage of correctly recalled friendly/enemy/ammunition counts served as measure of working memory</td></tr>
</table>

Table 7. Honeywell® Executive Summary of approach and results. (cont)

Bottleneck	Bottleneck Goal	Sample Tested	Team Results (by Task)		Mitigation	Practical Demo	Statistically Significant
Attention Allocation:	100%	n = 13	Message Comprehension (correct response to msg)	100%	*Comms Scheduler*	IHMC	$p < .05$
Attention Capacity:	100%	n = 13	% increase in number of ambushes avoided during navigation	380%	*Tactile Navigation Cueing*	IHMC	$p < .01$
Working Memory	100%	n = 10	% correct of memory for counts	155%	*Comms Scheduler*	CMU	$p < .04$

2.1.2 Background

Honeywell® Laboratories was selected to work on IWIIUS for the dismounted infantry domain. Table 7 is a summary of the approach and results to the FFW experiment conducted by the Honeywell® team. The team conducted two CVEs, one at the Institute of Human and Machine Cognition (IHMC), and the other at Carnegie Mellon University (CMU). The IHMC focus was on defining and measuring cognitive bottlenecks in the anticipated task environment for the FFW. CMU's focus was on addressing the unknown challenges of trying to measure cognitive state changes in task environments where physical activity will be extensive. The primary bottleneck addressed by Honeywell® was the Attention bottleneck (Note: the team also performed experiments addressing the Working Memory bottleneck at CMU). The attention resource and attention allocation metrics were tested at IHMC. Five gauges and associated biosensors were used to determine the attention resource and attention allocation gauge values (see Table 7 for complete listing).

Development and Analysis Team

The Honeywell® Laboratory team included CMU, City College of NY, Clemson University, Columbia University, Human Bionics, IHMC, Oregon Health and Sciences University, and UFI.

2.1.3 Operational Application—Future Force Warrior (FFW)

The team developed the JHAAS based upon operational environments expected of the U.S. Army's FFW program. FFW is the Army's flagship Science and Technology initiative to develop and demonstrate how revolutionary technology capabilities will transform the roles for, and capabilities of future dismounted infantry soldiers. FFW notional concepts seek to create a lightweight, overwhelmingly lethal, fully integrated individual combat system, including weapon, head-to-toe individual protection, netted communications, soldier-worn electrical power sources, and enhanced human physiological and cognitive performance. The program is aimed at providing unsurpassed individual and squad lethality, survivability, communications, and responsiveness—creating a formidable warrior in an invincible team. The FFW is a major pillar of the Future Force strategy, complementing the Future Combat Systems (FCS) program.

Relevance to FFW Application

FFW has a vision for Sensors and Communications: a "netted" soldier, small units and teams with robust communications, state-of-the-art distributed and fused sensors, organic tactical intelligence collection assets, enhanced situational understanding, on-the-move planning, and linkage to other force assets. Honeywell® Laboratories addresses these challenges with components of the JHAAS, specifically, the Communications Scheduler, Tactile Navigation Cueing, and the MEDEVAC Agent. The biosensors used to drive these cognitive-based systems will also feed another FFW

requirement—the onboard physiological/medical sensor suite with enhanced prompt casualty care that is the FFW Mobility Sustainability and Human Performance vision. The FFW is a major pillar of the Future Force strategy, complementing the FCS program.

"Hard Problems" for Dismounted Infantry

Soldiers are faced with highly dynamic task and operating environments—many sources of information and various contexts that have unpredictable delivery times. Information priorities change as context changes. With the advent of the FFW, the task environment demands increase dramatically due to netted communications moving real-time information through all echelons of command. This requires the FFW to perform the physical tasks expected of a warfighter today (navigate, communicate, identify, and engage), but also to process the ever-increasing amount of data provided by netted communications and sensors to ensure situational awareness for self as well as provide situational awareness to others up and down the chain of command. Additional information provided by netted communications is obviously valuable, but not at the cost of the soldier's ability to digest the data. As discussed in Table 7, cognitive research indicates that attention is a limited resource. In the FFW, with competing requirements for those attentional resources increasing because of the increasing data processing demands in a netted communications environment, attention is a resource that requires managing. The Honeywell® team developed and tested a system to address the Attention "bottleneck" problem.

Transition Customer

Honeywell® is part of the integrated "system-of-systems" approach taken to support the Army transformation to a soldier-centric force, making them well positioned to incorporate IWIIUS technologies into the FFW program. The Honeywell® team has been working consistently with the FFW Program and, in particular, the Human Performance Lead, Technology Program Office, and Land Warrior Block III Upgrade. Land Warrior is the Advanced Concept Technology Demonstration (ACTD) that the technology is targeted to transition to in the beginning of Fiscal Year (FY) 2008. The industry lead on the FFW program, General Dynamics Robotic Systems (GDRS) in conjunction with the Natick Soldier Center, will select the IWIIUS technologies that are mature enough to transition to Land Warrior. Technology insertion for FFW has a requirement to be identified by September 2007. The transition customer has identified a general metric of increased survivability and lethality measured against increased size, weight, power, cost, and complexity of any technology insertion.

Test Conditions

Figure 3 shows the general architecture used for the IHMC experiment (Attention bottleneck).

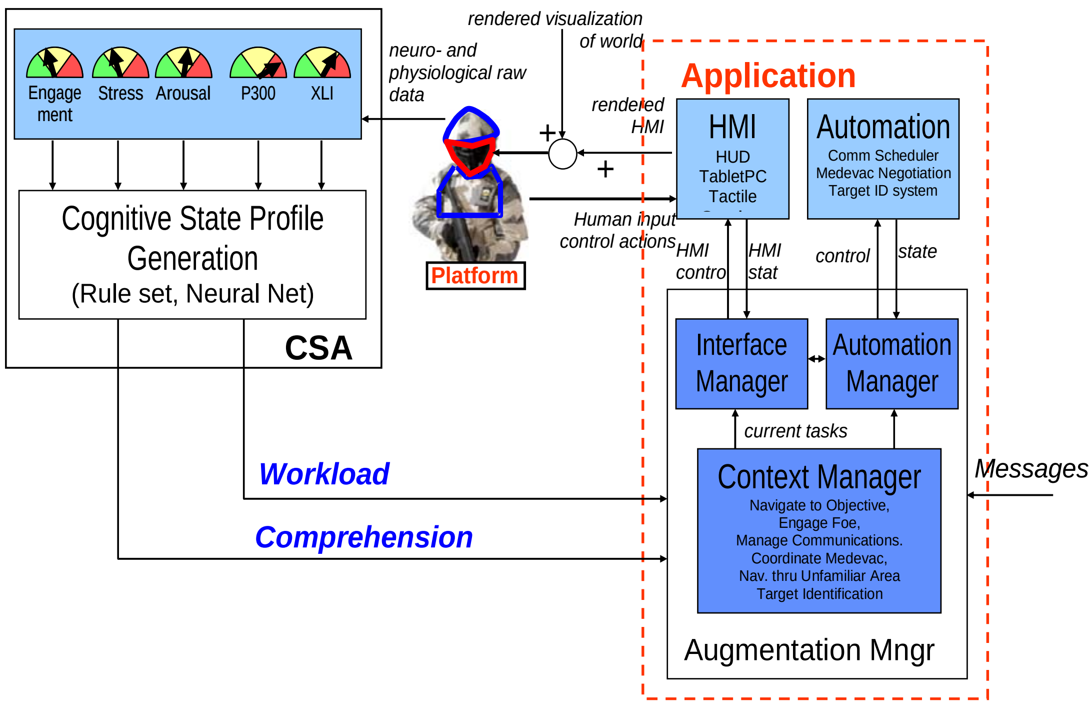

Figure 3. Team Honeywell® FFW CLIP architecture.

2.1.4 Methodology—IHMC

The test conditions for the Honeywell® team consisted of a simulation-based system (see Figure 3) that required participating in a "first-person shooter" scenario in a Military Operations on Urban Terrain (MOUT) environment. The basic task required the acting FFW to navigate to a pre-assigned objective. During this navigation mission, the participant was required to maintain situational awareness on enemy and friendly forces, manage communications with squad and upper echelons of command, avoid ambushes, complete a MEDEVAC, and engage the enemy when confronted. Participants were volunteer university students and staff. They had varying degrees of experience in PC gaming, but all had the same level of training on this task and had to meet a criterion level of performance before being used as an official test participant. The cognitive bottlenecks investigated during this set of experiments were attention resources and attention capacity.

Cognitive Bottleneck–Attention Capacity and Attention Allocation

Cognitive research indicates attention is a limited resource that has a fluctuating capacity. Available resources are allocated through active cognitive processing. Successfully augmenting Attention bottlenecks requires gauges that measure attention resource capacity and attention allocation of the available resources. Attention resource capacity was measured with an Inter-beat Interval (IBI) monitor, ECG, pupillometry, and GSR sensors. Attention allocation was measured with an EEG sensor. These sensors provided raw input that was processed to provide five gauges of cognitive state. The values of these gauges were then subjected to a rules-based system that determined the overall state of attention resources and attention allocation. Depending on the output of this rules-based system, the different mitigation strategies were used to enhance FFW performance.

Mitigation

Three types of mitigation were used to improve FFW performance. A *Communications Scheduler* was used to schedule and present messages based on the cognitive state profile, the message priority, and current context. Essentially, when the cognitive state profile indicated attention allocation was saturated (could not pay attention because of other attention priorities or overload), communications would be delayed until such time as attention resources were again available. A second mitigation, *Tactile Navigation Cueing*, used a 24-element tactor belt (15º resolution) and provided a pulse in desired navigation direction while frequency of pulses indicated proximity to objective. This mitigaion was turned on when attention capacity was limited. Finally, a *MEDEVAC Agent* mitigation executed medical evacuation of casualties with minimal information required from the FFW. The Agent was triggered when attention capacity was limited.

Independent and Dependent Variables

As noted in Table 1, this experiment used a single-factor repeated measures experimental design. The independent variable was Mitigation ON or Mitigation OFF. The dependent variable was the number of ambushes avoided. If the participant had sufficient attentional capacity, communicated warnings were processed and correct navigation was accomplished, allowing for minimum contact with enemy ambushes. If, however, capacity was insufficient, the participant would miss warnings and/or navigate into areas that were off the correct course to objective, significantly increasing encounters with enemy ambushes. The number of correct responses to queries was measured for the attention allocation-dependent variable. In this case, the participants' attention allocation may be saturated (paying attention to higher priorities or overloaded with too many things to pay attention to), stressing a decrement in their ability to respond to queries.

2.1.5 Methodology—CMU

In a second set of experiments conducted by the Honeywell® team, a more immersive environment was used. In this set of tests, a Virtual Reality (VR) system provided visualization through a set of head-mounted goggles and tracked the actual movement of the participant. This was the first step toward moving into a real "field" experiment where the sensors mounted on the FFW will be subjected to movement, shock, and other environmental extremes. The scenario required the participant to operate from a rooftop location and monitor surrounding buildings. The participant was required to identify and count friendly and enemy forces, eliminate enemy forces, and concurrently manage communications (report different counts to higher command). The cognitive bottleneck investigated with this experiment was working memory. The participants again were university students and had to meet a minimum performance level through training before being an official test participant.

Independent and Dependent Variables

As noted in Table 1, this experiment used a single-factor repeated measures experimental design. The independent variable was also Mitigation ON or Mitigation OFF. The dependent variable was percent correctly recalled of friendly/enemy/ammunition counts. The better the recall, the better working memory was functioning. If working memory had sufficient capacity and could process the numbers counted (e.g., interference in working memory would be using the same cognitive areas to manage counts and to answer a communications query—causing a capacity and processing conflict), the participant could easily keep track of counts and recall them when reporting to higher command. However, if the participant was in a conflicting working memory situation (see example in previous sentence) between counting and processing communications, both tasks suffered.

Cognitive Bottleneck—Working Memory

Working memory is that part of our cognitive system that we are consciously aware of at any given time. Working memory can be thought of as analogous to random access memory (RAM) on a computer. We have lots of memory storage capacity in our cognitive system, but the vast majority of that memory is permanent memory (analogous to hard-disk storage on a computer). When we communicate, we have to get a meaningful unit of speech or text into working memory to interpret it. The problem with slow or inaccurate communication is that working memory can only hold information for about 10 seconds and then it decays. If communication is delayed or requires considerable processing, by the time you get the last word of a meaningful dialog into working memory, the first words may have decayed. Messages would need to be repeated, making communications slow and laborious, and comprehension very difficult.

Mitigation

This set of experiments used one mitigation strategy. The Communications Scheduler rescheduled communications during high-working-memory workload states.

2.1.6 Results

The DARPA goal was to achieve a 100% improvement in the cognitive Attention bottleneck. The results obtained were statistically significant at the $p < 0.05$ level, and were done within system performance constraints specified at the start of IWIIUS Phase II. As can be seen in Table 7, this goal was matched or surpassed for those bottlenecks addressed by the Honeywell® team. In the Attention Allocation bottleneck (measured by message comprehension), a 100% improvement was observed, meaning that the FFW's ability to process communications while in a combat environment doubled. This has the potential effect of allowing improved situational awareness and therefore increased survivability and more effective force on force engagements. In the Attention Capacity bottleneck (measured by the number of avoided ambushes), a 380% improvement was observed, meaning that nearly four times as many ambushes were avoided as was found with the baseline condition due to the availability of the AugCog. This increase can be directly related to survivability of the FFW—with AugCog mitigation, the FFW will have better situational awareness, cognitively process those tasks that have direct bearing on survivability and lethality, and improve task performance times and accuracy.

2.1.7 Phase III Goals

Phase III will provide more challenges as IWIIUS technology is applied to real-world applications and under conditions of operational stress (in the field). Some challenges include the following:

- Under operational conditions of cognitive, physiological, and environmental stress, mitigate the impact of platform-specific stressors on cognition and information processing performance
- Real-time signal processing (artifact detection)—motion induces noise (artifacts) that makes cognitive state detection more difficult
- Context modeling with new field sensors—need sensors to understand the environment where decisions are made (in the field)
- Real-time cognitive state classification through neural networks (NN)—need to develop NNs tuned to individuals performing specific (identifiable) tasks

Probably more significant will be the transition from the laboratory environment to the field, which will include going to U.S. Army personnel in evaluations and experiments. System metrics will be developed to support FFW objectives (survivability/lethality) and performance on task (better

situation awareness, faster completion of task, improved survivability, increased lethality) will be the metric challenges in Phase III. A technology metric will be reliable classifications (90% correct classification over blocks of time) in a “field” environment.

More key to the success of Phase III and the future use of IWIIUS technology will be user acceptance. The FFW goals are clear—survivability and lethality must be enhanced for any technology to be acceptable to the future warfighter. Phase II has shown that the promise is there; Phase III will have the challenge of taking the next step toward warfighter employment.

2.2 U.S. MARINE CORPS—MARINE AIR GROUND TASK FORCE (MAGTF) LIGHT ARMORED VEHICLE (LAV)

2.2.1 Concept Validation Experiment (CVE) Analysis Report Summary

Table 8. DaimlerChrysler® Executive Summary of approach and results.

<table>
<tr><td colspan="4">Concept Development and Analysis Team Prime: DaimlerChrysler Corporation (DCC)</td></tr>
<tr><td colspan="4">Application: MAGTF Light Armored Vehicle (LAV)</td></tr>
<tr><td colspan="4">Hard Problems:
• Multi-tasking under high stress: Move, shoot, and communicate (performed all simultaneously by the crew members)
• Sensory input bottlenecks operationally defined in terms of tasks that compete for limited sensory processing resources. Driving requires high levels of visual processing—need to present additional tasks through alternate modalities, e.g., auditory. Need to validate
• Cognitive bottlenecks may also be task-specific—must operationally define and validate in operational context to predict if augmentation is going to be effective</td></tr>
<tr><td colspan="4">Transition:
• Target Program: MEFFV: Marc Miller, USMC Vehicles Branch—Code 2120, NSWC Carderock</td></tr>
<tr><td colspan="4">Test Conditions:</td></tr>
<tr><td>Scenario</td><td colspan="3">• Driving under real conditions on German highways
• Tasks create high demands on working memory, auditory and visual sensory processing
o Primary task was to drive (high demands on visual processing and working memory)
o Secondary tasks include listening to situational brief and questions, performing navigational math, executing driving maneuvers, acknowledging auditory or visual commands (creating high demands for auditory processing, working memory, visual processing)</td></tr>
<tr><td>Participants</td><td colspan="3">• $N = 5$
• Male, right-handed, DCC test drivers, average age of 30 years</td></tr>
<tr><td rowspan="4">Gauges</td><td>Gauge and Developer:</td><td>Tested:</td><td>Used:</td></tr>
<tr><td>EEG: auditory sensory input gauge
(FIRST, Berlin, Germany)</td><td>✓</td><td>✓</td></tr>
<tr><td>EEG: working memory gauge
(FIRST, Berlin, Germany)</td><td>✓</td><td>✓</td></tr>
<tr><td>Context + driving behavior + seat posture:
visual sensory input gauge
(Sandia Ntl. Lab, Albuquerque, NM;
University of Pittsburgh, PA)</td><td>✓</td><td>✓</td></tr>
<tr><td>Integration Architecture</td><td colspan="3">• Sensors connected to stand-alone gauge processors
• Gauge outputs shared over network through vehicle's CAN data-bus technology
• Cognitive states based on specific task demands. Linear Discriminate Analysis based on EEG data and neural network analysis based on context data are used to define high/low states
• EEG classifiers finalized during training session for each participant</td></tr>
<tr><td>Mitigation Rationale</td><td colspan="3">• Modality switch - Auditory to Visual. This strategy was used when the Driving-Maneuvers task was performed (implying that auditory modality was available)
• Scheduling - Delayed presentation of information. This strategy was used when Situational-Brief or Navigational-Math tasks were performed, i.e., when visual and auditory modality were at capacity</td></tr>
</table>

Table 8. DaimlerChrysler® Executive Summary of approach and results. (cont)

<table>
<tr><td colspan="2">Experimental Design</td><td colspan="6">Each participant performed one Baseline Session (without mitigation system) and one AugCog Session (with mitigation system), 2 hours each
Single-factor (mitigation on/off) repeated measures</td></tr>
<tr><td colspan="2">Independent Variables</td><td colspan="6">Mitigation (none, augmented)</td></tr>
<tr><td colspan="2">Dependent Variables</td><td colspan="6">Information-processing performance (processing speed and accuracy) on competing secondary task (auditory or visual commands, respectively)</td></tr>
<tr><th>Bottleneck</th><th>Bottleneck Goal</th><th>Sample Tested</th><th colspan="2">Team Results (by Task)</th><th>Mitigation</th><th>Practical Demo</th><th>Statistically Significant</th></tr>
<tr><td>Sensory Input (Auditory)</td><td>100%</td><td>N = 5</td><td>auditory commands</td><td>108%</td><td>scheduling</td><td>✓</td><td rowspan="3">one-tailed Wilcoxon (paired rank-sum) test:
T (15) = 27, p < 0.05</td></tr>
<tr><td>Sensory Input (Visual)</td><td>100%</td><td>N = 5</td><td>visual commands</td><td>72%</td><td>modality switch</td><td>✓</td></tr>
<tr><td>Working Memory</td><td>500%</td><td>N = 5</td><td>auditory commands</td><td>103%</td><td>scheduling</td><td>✓</td></tr>
</table>

2.2.2 Background

DaimlerChrysler Corporation (DCC) was selected to work on IWIIUS for the combat vehicle domain. Table 8 is a summary of the approach and results of manipulating the cognitive state of an active driver. The environment and tasks were structured to replicate a military environment while maintaining experimental controls (e.g., test participants, vehicle instrumentation, and repeatability of driving environment). The primary cognitive bottleneck assigned to DCC was the Sensory Input bottleneck. Three gauges and associated sensors were used to determine the cognitive loading (general workload), sensory inputs (verbal or spatial), and task context (turning, changing lanes, etc.)

Development and Analysis Team

The DCC team included DaimlerChrysler AG, University of Pittsburgh, Fraunhofer Institute FIRST, Sandia National Laboratories, and Transferzentrum für Mikroelektronik.

2.2.3 Operational Application—Light Armored Vehicle (LAV)

The MEFFV is a combat vehicle replacement project designed to provide the capabilities presently conferred by the LAV family and the M1A1 Main Battle Tank. It is envisioned that this family of vehicles will facilitate and enhance the capabilities of Expeditionary Maneuver Warfare through technologies to significantly improve efficiency and lessen the impact of operational and tactical logistics. The family of vehicles will be designed to maximize deployability options while retaining the requisite combat capabilities (lethality, survivability, mobility, sustainability) to perform the roles of the vehicles replaced. MEFFV should replace the LAV and tank fleets when they reach their respective end-of-service dates (2015 and 2020, respectively).

Relevance to MEFFV Application

As stated above, MEFFV will replace the United States Marine Corps' (USMC) current family of LAVs and the M1A1 Main Battle Tank. However, the intent is not a one for one replacement; the expectation is a modular design concept that will maximize component commonality to minimize operations, training, and maintenance costs and provide potential manpower structure savings. Additionally, the MEFFV will be expected to take advantage of network-centric warfare. Thus, the MEFFV program is faced with a growing amount of available information through advanced networked sensors and communications. An additional requirement is to provide a reduction in manpower for future vehicles. The warfighter will have to deal with the highly visual task

of driving a vehicle while simultaneously dealing with communications and sensor management. Allowing the warfighter to accomplish multiple and competing tasks will require the vehicle and information interfaces to have driver's state "awareness"—both context (e.g., maneuvering around obstacles, avoiding enemy contact, maintaining formation with other vehicles, etc.) and cognitive (e.g., processing spatial information, processing verbal information).

"Hard Problems" for MEFFV

Multi-tasking under high stress—move, shoot, and communicate, each performed simultaneously by the warfighter—is the fundamental hard problem for the MEFFV. Reducing the number of crew members from current manning exacerbates the problem. The warfighter has a limited capacity (bottleneck) for processing sensory input. Sensory Input bottlenecks are operationally defined in terms of tasks that compete for those limited sensory processing resources. Driving requires high levels of visual processing, depending on driving task or context. Thus, additional tasking (communications, sensor management) may need to be presented through alternate modalities, e.g., auditory. When and how to shift between modalities for competing tasks (simultaneous visual or verbal) and the benefit of mitigation to operational performance is the "hard problem" that the DCC team is addressing.

Transition Customer

The DCC team is working with the Office of Naval Research, the Marine Corps Systems Command MEFFV program office, the USMC Vehicles Branch (Code 2120), and Naval Surface Warfare Center, Carderock Division. The Carderock Division is contributing to the development of the MEFFV by looking at technologies to insert into the MEFFV program. The USMC Vehicles Branch is working with DCC to provide operational context for further developing IWIIUS technologies.

Test Conditions

Figure 4 shows the general architecture used by the DCC team.

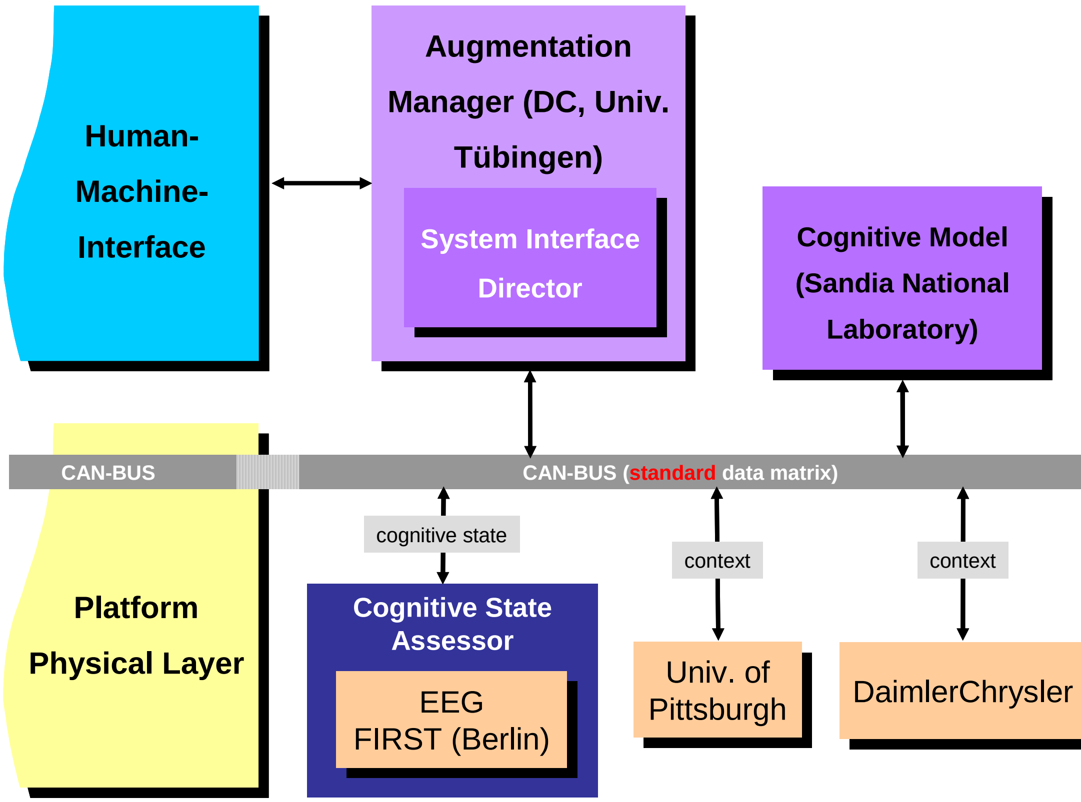

Figure 4. Team DCC CLIP architecture.

2.2.4 Methodology

The test conditions for the DCC team consisted of an instrumented Mercedes Benz® S class vehicle driving on German highways in and around Stuttgart, Germany. The primary task was to drive the vehicle safely and navigate between waypoints. Competing tasks were then introduced. These consisted of listening to a situation brief and responding to questions, performing navigational mathematics, executing directed driving maneuvers, and acknowledging auditory or visual commands. The primary task provided a high demand for visual sensory processing. The secondary tasks provided competing visual tasks to the primary tasks and provided competing tasks for auditory (or verbal sensory input) processing.

Cognitive Bottleneck—Sensory Input

The DCC team addressed the Sensory Input cognitive bottleneck. This bottleneck can be described as the cognitive areas necessary for processing different sensory inputs such as verbal and spatial inputs. Cognitive science suggests that most processing areas of the brain are synchronous. Thus, if the area responsible for processing verbal inputs is "busy," additional verbal inputs will potentially be missed or ignored. However, the brain can also parallel process; thus, if the verbal processing areas are busy and new verbal inputs are available, it is believed that a modality switch—changing verbal input to spatial input—would allow immediate processing of the new verbal input, but in another modality. Another method of handling competing verbal (or other modalities) inputs would be to use a scheduling device that would know when verbal processing was "busy" and when it was "available." The DCC team used these concepts and additional information from context sensors to develop their experimental theories and mitigations to optimize the warfighter/driver performance.

Mitigation

Table 8 shows the mitigation strategies used during the CVE experiment.

- ***Mitigation 1.*** Modality switch (auditory to visual). This strategy was used when the Driving-Maneuvers task was performed (implying that auditory modality was available).
- ***Mitigation 2.*** Scheduling (delay presentation of information). This strategy was used when Situational-Brief or Navigational-Math tasks were performed, i.e., when visual and auditory modality were at capacity.

Mitigation 1 provided the capability, while the vehicle was maneuvered (high spatial processing task), to change additional spatial tasks (competing with driver maneuvering) to another modality, in this case, auditory (verbal-processing) commands. Mitigation 2 was used when the participant was using normal driving skills, but given a situation brief or asked to perform a navigational mathematical problem. While listening to the situation brief, the participant's auditory or verbal processing was at or near capacity. Introducing additional verbal tasks would cause those tasks to be ignored or cause a decrement in performance on both verbal tasks. Given the known state of the participants' sensory processing, a scheduling mitigation technique was implemented for verbal tasks.

Independent and Dependent Variables

As noted in Table 8, this experiment used a single-factor repeated measures experimental design. The dependent variable was Mitigation ON or Mitigation OFF. The dependent variable was the information-processing performance (processing speed and accuracy) on a competing secondary task. Essentially, the participant, while maneuvering the vehicle through normal highway traffic, was presented with competing tasks that required spatial (visual) or verbal (auditory) processing—how well the participant processed these competing tasks (accuracy) and how quickly the participant performed the tasks was the performance measurement for this experiment.

2.2.5 Results

The DARPA goal was to achieve a 100% improvement in the cognitive Sensory Input bottleneck. The results obtained were statistically significant at the $p < 0.05$ level and were done within system performance constraints specified at the start of Phase II. As can be seen in Table 8, operator performance improved 108% when the mitigation was activated in dealing with the auditory/verbal sensory input. The spatial or visual sensory input resulted in a 72% increase. This result is explained when one considers that the primary operating environment is driving—highly visual. This environment leads to the conclusion that spare capacity is limited in the visual/spatial channel and a 72% improvement is actually quite remarkable. With the present prototype, DCC demonstrated that it is possible to reliably detect cognitive state changes and that this information allows significant improvement in operator performance. This capability should allow a warfighter to process two to three times more information as compared to a typical combat vehicle driver of today.

2.2.6 Phase III Goals

The Phase III goal is to mitigate the impact of platform-specific stressors on cognition and information-processing performance while under operational conditions of cognitive, physiological, and environmental stress. In light of this main goal, susceptibility of EEG-based gauges to artifacts caused by mechanical vibrations or shocks must be addressed. In a G-Class (combat) vehicle used on offroad courses, artifacts may be expected to be of a different nature than in the current S-Class vehicle. Thus, it may be necessary to develop online artifact rejection algorithms that allow sufficient cleaning of the data before passing them to the cognitive state classifiers. In addition, future

recording techniques (e.g., contact-free measurement) may be less susceptible to movement, vibration, or shock artifacts. Additionally, DCC plans to migrate their system to the operational environment of the MEFFV in collaboration with the USMC Vehicles Branch. This plan will require adapting the operational environment tasks to USMC specifications and to adapt gauges to those tasks.

More significantly, a new challenge for Phase III will be to simultaneously monitor the cognitive states of multiple operators within a team and to develop significantly more sophisticated mitigation algorithms to balance tasking across the whole team. The goal will be to demonstrate the system's capability of dynamically distributing crew workload among driver, commander, and vehicle, thus increasing the crew's operational performance and safety.

2.3 U.S. NAVY—TACTICAL STRIKE COORDINATOR (TSC) FOR THE TACTICAL TOMAHAWK WEAPONS CONTROL SYSTEM (TTWCS)

2.3.1 Concept Validation Experiment (CVE) Analysis Report Summary

Table 9. Lockheed Martin® Executive Summary of approach and results.

<table>
<tr><td colspan="4">Team: Lockheed Martin® Advanced Technology Laboratory (LMATL)</td></tr>
<tr><td colspan="4">Application: Tactical Tomahawk—Tactical Strike Coordinator (TSC)</td></tr>
<tr><td colspan="4">Hard Problems:
• TSC anticipated as taking on new functions to support real-time mission re-targeting. Will require single person to do what three people are currently doing
• Significant re-planning components with simultaneous monitoring of ongoing missile missions will overload working memory
• Must remember missile capabilities, potential track conflicts, which missiles can service which targets, variable time constraints, and long–term implications to future missions</td></tr>
<tr><td colspan="4">Transition:
• TTWCS—PMA 282, NAVAIR's Cruise Missile Weapons Control Systems Program Office, Advanced Concepts Group
• POC: LCDR Eric LeGear, Advanced Concepts, CAPT Sullivan, PMA 282</td></tr>
<tr><td colspan="4">Test Conditions:</td></tr>
<tr><td>Scenario</td><td colspan="3">• TTWCS desktop simulation
• Task Demands:
o Location (Spatial Memory) Task: When augmented video display fails, remember which missiles are striking which targets
o Alert (Situation Awareness) Task: Questions asked through text in Chat window re: current situation
o Retarget (Working Memory) Task: Emergent target tracks appear on video display. Participant must quickly process time and capabilities constraints for numerous missiles and targets</td></tr>
<tr><td>Participants</td><td colspan="3">• N = 12
• LMATL personnel, not experts</td></tr>
<tr><td rowspan="6">Gauges</td><td>Sensor:</td><td>Tested</td><td>Used:</td></tr>
<tr><td>GSR: Anthrotronix</td><td>✓</td><td>✓ (data only)</td></tr>
<tr><td>EKG: Anthrotronix</td><td>✓</td><td>✓ (data only)</td></tr>
<tr><td>EEG: Advanced Brain Monitoring</td><td>✓</td><td>✓ (data only)</td></tr>
<tr><td>Pupillometry: Index of Cognitive Activity (ICA) – Eye Tracking, Inc.</td><td>✓</td><td>✓</td></tr>
<tr><td>fNIR – Drexel University.</td><td>✓</td><td></td></tr>
<tr><td>Integration Architecture</td><td colspan="3">• Cognitive State Assessor (CSA) processor uses neural network to identify two gauge values (verbal and spatial working memory—based on a mix of preprocessed data and ICA gauge output)
• Performance Augmentation through PACE architecture is rule-based system determining what augmentation should be triggered and when</td></tr>
<tr><td>Mitigation Rationale</td><td colspan="3">• Intelligent Sequencing—Change the order of sequentially presented verbal and spatial tasks</td></tr>
<tr><td>Experimental Design</td><td colspan="3">• Single-factor (mitigation on/off) repeated measures</td></tr>
</table>

Table 9. Lockheed Martin® Executive Summary of approach and results. (cont)

Independent Variables		• Mitigation (none, augmented)				
Dependent Variables		• Performance score for retargeting task with/without augmentation.				
Bottleneck	**Bottleneck Goal**	**Sample Tested**	**Team Results**	**Mitigation**	**Practical Demo**	**Statistically Significant**
Working Memory	500%	$n = 12$	642%	*Intelligent Sequencing*	✓	$t\,(11) = 5.84$, $p < .001$

2.3.2 Background

The Lockheed Martin® analysis report discusses the Cognitive Task Environment(s), human state gauges, and biosensors used; research methods; integrated prototype system design; and empirical results. LMATL was the chosen performer to work on IWIIUS in the Tactical Tomahawk Weapons Control System (TTWCS) domain. The LMATL focus was on the cognitive task environment of the TSC; Table 9 is a summary of the approach and results of manipulating the cognitive state of the operator. The primary bottleneck addressed by LMATL was the Working Memory bottleneck. Five gauges and associated biosensors were used to condense to two gauge values (verbal and spatial working memory) through a neural network.

Development and Analysis Team

The Lockheed Martin® team was led by LMATL and included Design Interactive, Anthrotronix, Advanced Brain Monitoring, Drexel University, University of Virginia, and Eyetracking, Inc. For Phase II, the team developed the simulated TTWCS within a CLIP-based on operational environments expected of the U.S. Navy’s Tactical Tomahawk program.

2.3.3 Operational Application—TTWCS Tactical Strike Coordinator (TSC)

TTWCS is the Navy’s evolutionary HCI development approach undertaken by the Advanced Concepts Group under the Cruise Missile Weapons Control Systems Program Office (PMA-282) to combine several interfaces into an integrated land-attack presentation layer. TTWCS is a fully integrated Joint Service partner, exchanging information and battle graphics with other service systems. The new TTWCS effort is being integrated by Lockheed Martin® Integrated Systems and Solutions (IS&S). With the introduction of the Tomahawk Block IV upgrade, new challenges are being placed on the planners and executers of a Tomahawk Land-Attack Missile (TLAM) event. The Tactical Tomahawk will use onboard mission planning, in-flight retargeting, and battle damage assessment capabilities. The goals for the upgraded TLAM are to service high-priority, time-critical targets, with a goal of less than 10 minutes from target identification to target destruction.

“Hard Problem” for the TSC

The introduction of the new Tactical Tomahawk means that a layer of human control will be needed where none previously existed. The Tactical Tomahawk case illustrates a perplexing problem for cognitive systems engineers designing a supervisory control system to support monitoring and resource allocation.

The TSC has overall responsibility for TLAM operations, determining mission and missile requirements, which launch a platform to task. In the future, the TSC will be expected to do the work that three operators currently perform. The new capabilities of retargeting, re-planning, and simultaneous monitoring of missions in flight will overload working memory of a single TSC. Working memory is a capacity-limited and time-constrained resource. The TSC must remember missile configuration, look for potential track conflicts, ensure proper missile-to-target pairing, and account for temporal

constraints and the implications of current missions on future mission planning. These tasks will compete for use of working memory. The hard problem for the LMATL team is maximizing the efficiency of the operator's working memory while increasing operational performance—doing the work of three with one.

Transition Customer

The LMATL Team has been working with the Lockheed Martin® IS&S Division TTWCS Program internally and externally with Naval Air Systems Command's (NAVAIR) Advanced Concept Group under the Cruise Missile Weapons Control Systems Program Office (PMA-282). The ability to redirect an in-flight missile, loiter a missile to allow quick reaction re-planning, and provide battle damage assessment has been successfully brought forward with the Block IV Tomahawk and through the development of TTWCS. Design changes are planned for later versions of TTWCS to improve the HCI (this is where LMATL comes in with AugCog). LMATL cognitive research will improve TTWCS to achieve a reduction in operator workload through mitigation techniques triggered by a biosensor-driven neural network in a closed loop, which will ultimately improve operator performance. The transition customer has identified a general metric of the TSC doing the work of three Tomahawk operators.

Test Conditions

The LMATL prototype system is designed around the Performance Augmentation through Cognitive Enhancement (PACE) architecture (Figure 5). PACE is a highly reusable architecture that manages user tasks and allows implementing various mitigation strategies in a domain-independent fashion. PACE consists of several components that are entirely domain-independent and several that are designed to be extended for a particular domain.

Interacting with PACE is the prototype jTTWCS (Java Tactical Tomahawk Weapon Control System), which presents a user interface allowing the operator to perform the TTWCS tasks of missile monitoring and retargeting.

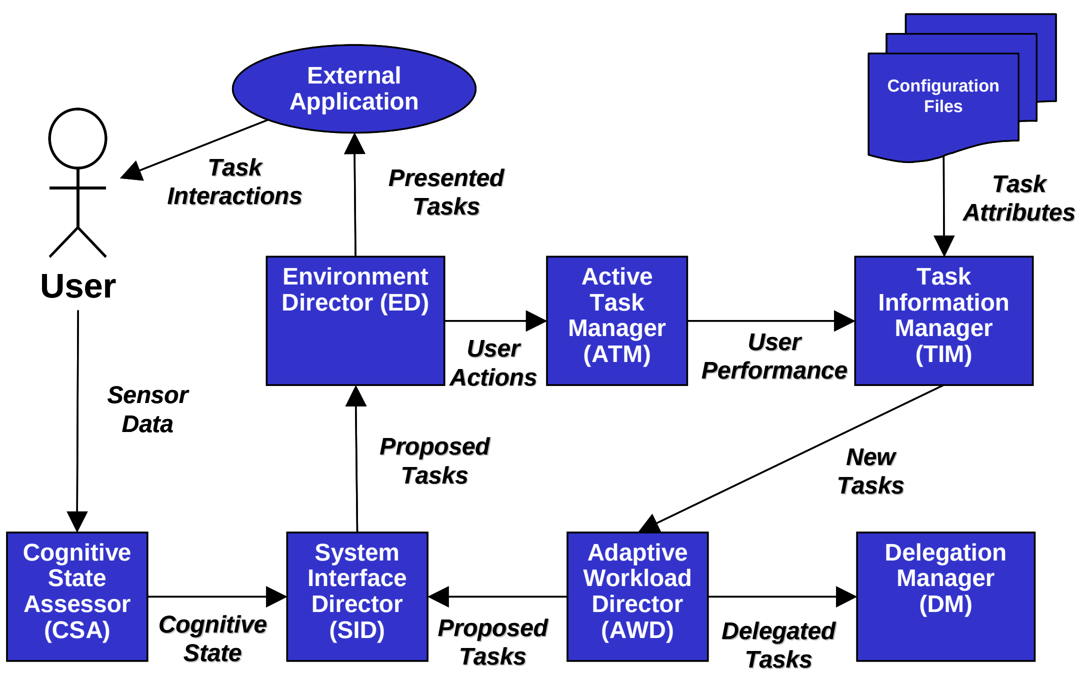

Figure 5. PACE architecture—major components and key interactions.

2.3.4 Methodology

The test conditions for the LMATL team consisted of a desktop TTWCS simulation workstation system (see architecture in Figure 5) that required the operator to manage several TLAM missions (already in progress) simultaneously. The TSC monitors and adjusts the TLAM strikes as events unfold. TSC tasks include re-targeting missiles, assessing missile coverage zones and remembering which missiles are striking which targets, and responding to questions presented through a chat interface. The participants were LMATL personnel, not U.S. Navy TLAM experts.

Cognitive Bottleneck—Working Memory

Working memory is that part of the human cognitive system that one is consciously aware of at any time. Working memory can be thought of as analogous to RAM memory on a computer. While memory storage capacity in the human cognitive system is vast, the majority is permanent memory (analogous to hard-disk storage on a computer). Meaningful communication requires input of a unit of speech or text into working memory to interpret it. Cognitive research indicates that working memory contains two unique components: verbal and spatial. Successfully augmenting a Working Memory bottleneck requires gauges that measure the spatial and/or verbal working memory.

The LMATL research focused on measuring verbal and spatial working memory through a neural network that produced two gauge values based on a mix of pre-processed data and ICA gauge output. The gauges were based on the Pupillometry Index of Cognitive Activity (ICA) (Eye Tracking, Inc.), physiological sensors (GSR, ECG) that provided general workload, and EEG that provided localization of verbal/spatial working memory. Gauge values were then applied to a rule-based system that determined when the augmentation should be turned on or off.

Mitigation

Intelligent sequencing improved TSC performance. The system received updates regarding the operator's current use of spatial and verbal working memory through the Artificial Neural Network (ANN). When the new task was proposed, the system decided to either present the task immediately or at a later time when the operator's working memory was less tasked. When the system recognized that the operator was simultaneously engaged in the re-targeting task and the message alert task, *and* was experiencing a verbal working memory overload, the alerts would be deferred until the location task (highly spatial) was presented, and then the verbal alerts were delayed.

Independent and Dependent Variables

The experiment used a single-factor repeated measures experimental design. The independent variable was Mitigation ON or Mitigation OFF. The dependent variable was the performance score for the TLAM re-targeting task (weighted by complexity). Emergent target tracks appear on the TTWCS display, the TSC must process weapon profile (time of flight) of TLAMs already in flight to previously assigned targets, and the number of TLAMs required for the new emergent target (1, 2, or 3). Based on those factors, the operator must decide which in-flight TLAMs to re-target to what higher priority emergent targets.

2.3.5 Results

The DARPA goal was to achieve a 500% improvement in the Working Memory bottleneck. The Working Memory (verbal) bottleneck was measured by number of successfully serviced emergent targets weighted by target complexity. The results obtained were statistically significant at the $p < 0.001$ level, and were done within system performance constraints specified at the start of IWIIUS Phase II. As can be seen in Table 9, this goal was surpassed for the bottleneck addressed

by the LMATL team. In the Working Memory bottleneck (measured by the retargeting task), a 642% improvement was observed, meaning that the TSC's ability to re-target TLAMs in flight to new emergent targets was increased over sixfold. This improvement occurred in the presence of competing tasks to answer alerts (chat questions) that tested the participant's situational awareness and ability to assess coverage zones in the location task, which has the potential to allow a TSC to do all tasks related to execution of a multiple TLAM launch that currently is accomplished in several layers by three different operators.

2.3.6 Phase III Goals

Phase III will provide more challenges as IWIIUS technology is applied to increasingly mature TTWCS test beds in more operationally defined scenarios with refined task representation. Some other challenges include the following:

- Under operational conditions of cognitive, physiological, and environmental stress, mitigate the impact of platform-specific stressors on cognition and information processing performance
- Moving as many biosensors off the head as possible—eye pupillometry and tracking off the head
- Inserting remaining sensors in a single integrated helmet design
- Integrating the fNIR/EEG sensors
- Developing truly task-independent gauges
- Developing additional mitigation strategies for other bottlenecks
- Improving Cognitive State Assessor "fieldability" and flexibility
- Evaluating aspects of task interference
- Developing an error-prediction and early warning gauge

Finally, system degradation will be addressed. In its current configuration, system performance will degrade significantly with the loss of one sensor. This issue will be addressed in the future by training the neural network with a more robust training set, including situations with inactive sensors.

2.4 AIR FORCE

2.4.1 U.S. Air Force—Unmanned Air Vehicle (UAV) Operator for the Joint Unmanned Combat Air System (J-UCAS) Concept Validation Experiment (CVE) Analysis Report Summary

Table 10. Boeing® Executive Summary of approach and results.

<table>
<tr><td colspan="4">Team: Boeing®</td></tr>
<tr><td colspan="4">Application: Unmanned Air Vehicle (UAV) Operator (combat)</td></tr>
<tr><td colspan="4">Hard Problems:
• UAVs currently require multiple operators to control single UAV. J-UCAS requires single operator and multiple vehicles
• Controlling multiple UAVs is cognitively demanding because of constant context shifting within and between tasks for each vehicle and between vehicles</td></tr>
<tr><td colspan="4">Transition:
• Joint – Unmanned Combat Air System (J-UCAS)
• POC: Mark Pitarys - Deputy Program Manager J-UCAS (DARPA)</td></tr>
<tr><td colspan="4">Test Conditions:</td></tr>
<tr><td>Scenario</td><td colspan="3">• UAV Operator workstation—managing 12[2] vehicles
• Managing multiple vehicles and keeping track of multiple tasks and procedures for each vehicle under time constraints, creating high demands on Executive Function (cognitive processing capacity)
• Complex task environment with competing tasks:
o Task: Tactical Situation Display (TSD)—Process multiple vehicles—target identification, weapons pairing, and attack
o Task: Vehicle Health Task (VHT)—Process pop-up failures and address maintenance/logistic issues</td></tr>
<tr><td>Participants</td><td colspan="3">• N = 3
• Boeing® & USAF Engineers: Highly trained, right-handed males</td></tr>
<tr><td rowspan="10">Gauges</td><td>Gauge & Developer:</td><td>Tested:</td><td>Used:</td></tr>
<tr><td>NuWAM TSD part-task (AFRL)</td><td>✓</td><td>✓</td></tr>
<tr><td>NuWAM VHT part-task (AFRL)</td><td>✓</td><td></td></tr>
<tr><td>SPC TSD part-task (Boeing®)</td><td>✓</td><td>✓</td></tr>
<tr><td>SPC VHT part-task (Boeing®)</td><td>✓</td><td>✓</td></tr>
<tr><td>NovaSol: fNIR, tested and used (SPC and NuWAM)</td><td>✓</td><td>✓</td></tr>
<tr><td>ETI: Eyetracking/Pupillometry (ICA), tested and used (SPC and NuWAM)</td><td>✓</td><td>✓</td></tr>
<tr><td>AFRL: EEG, ECG, EOG, NN, tested and used (NuWAM)</td><td>✓</td><td>✓</td></tr>
<tr><td>QUASAR – dry electrodes, tested and used (NuWAM)</td><td>✓</td><td>✓</td></tr>
<tr><td>Clemson: Arousal Meter, tested and used (NuWAM)</td><td>✓</td><td>✓</td></tr>
</table>

[2] J-UCAS target is one operator controlling four air vehicles. The AugCog goal is one operator doing the work of three. Thus the scenario design was one operator operating 12 vehicles.

Table 10. Boeing® Executive Summary of approach and results. (cont)

Integration Architecture	• Sensor data collected/distributed via networked database
	• Cognitive State Assessor (CSA) inputs sensor data from database
	• CSA computes TSD and VHT gauge values back to database
	  o Indicates high or low task derived (TSD or VHT) cognitive processing load
	• Augmentation Manager combines gauge data and context data to determine mitigation triggers based on rules
	  o Context is determined by operator behaviors and number of impending critical tasks
	    ▪ Context gauges were developed to complement each cognitive gauge based on number and type of operator inputs expected by the system for pending tasks
	  o The mitigation is turned on when the cognitive gauge and the context gauge agree
	  o A predefined set of mitigations is assigned to a single gauge[3]
	  o Mitigation initiation and termination; a joint function of gauge output and computed context

Mitigation Rationale	• During CVE, a predefined set of mitigations was triggered by the AM (dependent on cognitive state and context gauges)
Experimental Design	• Competing tasks paradigm • Within subject, 2 x 1 repeated measure
Independent Variables	• Augmented versus non-augmented
Dependent Variables	• Executive Function: TSD—number of bombs on target • Working memory: VHT—number of tasks missed • Sensory input: number of events performed simultaneously • Attention: number of detected and engaged pop-up events

Bottleneck	Bottleneck Goal	Sample Tested	Team Results (by Task)	*Mitigation	Practical Demo	Statistically Significant[4]
Working Memory	500%	(n = 3).	680%	*Mitigation 1*	✓	$W(6) = -21, p < 0.025$
Executive Function	100%	(n = 3).	241%	*Mitigations 2, 3, 5, 6*	✓	$W(6) =-19, p<0.05$
Sensory Input	100%	(n = 3).	283%	*Mitigations 1, 2, 3, 4, 5, 6, 7 and 8*	✓	$W(6) = -21, p < 0.025$
Attention	100%	(n = 3).	750%	*Mitigations 2, 3,4, 5, 6*	✓	$W(6) = -21, p < 0.025$

*See Table 11 on next page for mitigation guide

[3] Each gauge can have multiple mitigations.
[4] (Wilcoxen – signed pair)

Table 11. Mitigation guide.

Task	Mitigation Name	Bottleneck(s) Mitigated	Mitigation Explanation
1-VHT	Alert Manager	Working Memory	The Alert Manager is a dialog box that collects all of the currently active vehicle alerts into a single list sorted by priority.
2-TSD	De-clutter	Executive Function, Sensory Input, Attention	The de-clutter mitigation places a “fog layer” over the map, thereby partially obscuring the map and the vehicle flight path lines. This makes the details of interest (e.g., air vehicles and targets) much easier to see.
3-TSD	Earcons	Executive Function, Sensory Input, Attention	Earcons are brief, distinctive sounds that are typically associated with specific mission events. For example, a camera shutter “click” sound is presented to signal initiation of a Capture SAR command. Auditory cue consistent with event initiation (redundant to menu selection – intent to reduce error rate with auditory task initiation cue).
4-TSD	Time Critical Target (TCT) Voice	Sensory Input, Attention	The time-critical voice mitigation is a computer-generated female voice that speaks the words “Tiger leader, we’ve detected a time critical target” whenever a time-critical target is activated. Auditory alert message is specific to TCT.
5-TSD	Bookmark	Executive Function, Sensory Input, Attention	The bookmark mitigation provides the operator with some assistance in determining the most expedient “next” action on the Tactical Situation Display. Each strike package has an icon traveling with it at the center of mass of the four air vehicles. The circular center section of the icon is color-coded red, yellow, or green, depending on the relative urgency of the most urgent vehicle for each of the strike packages—visual cue for recommending next UAV operator tasks.
6-TSD	Unified Bookmark	Executive Function, Sensory Input, Attention	The unified bookmark expands on the basic bookmark by including in its logic the additional considerations of Vehicle Health Task alerts. A red square is placed on the next recommended action–visual cue for next UAV operator task.
7-TSD	UAV Menu Tokens	Sensory Input	The UAV Menu Tokens mitigation placed two “tokens” on each air vehicle icon. The tokens were small squares. One token was red and one was green. The red token corresponded to the Direct Attack option on the drop down menu and the green token corresponded to the SAR/Attack option-menu shortcut.
8-VHT	Vehicle Health Tones	Sensory Input	The Vehicle Health Tones mitigation presented a unique computer-generated tone for each strike package whenever a vehicle health problem was detected—auditory cue to a pending VHT and localization (which UAV SP).

2.4.2 Background

The Boeing® team analysis report discusses the Cognitive Task Environment(s), human state gauges and biosensors used, research methods, integrated prototype system design, and empirical results. Boeing® Phantom Works was the chosen performer to work on IWIIUS in an Unmanned Air Vehicle (UAV) domain. Table 10 is a summary of the approach and results of manipulating the cognitive state of a Joint Unmanned Combat Air System (J-UCAS) UAV operator. The primary bottleneck assigned to Boeing® was the Executive Function bottleneck; however, the team also researched Working Memory, Sensory Input, and Attention. The Boeing® research environment was very complex, with biosensors fed to an ANN for Executive Function and Attention, and separately through another process called Statistical Process Control (SPC) for Working Memory and Sensory Input. For the Executive Function bottleneck, three biosensors were used: EEG, ECG, and pupilometry ICA.

Development and Analysis Team

The Boeing® team was led by Boeing® and included Air Force Research Laboratory (AFRL), NOVASOL, University of Clemson, and Eyetracking, Inc. For Phase II, the team developed the simulated J-UCAS workstation within a CLIP based on operational environments expected of the U.S. Air Force's Unmanned Combat Air System.

2.4.3 Operational Application—Unmanned Air Vehicle (UAV) Operator

The J-UCAS program is a joint DARPA/Air Force/Navy effort to demonstrate the technical feasibility, military utility, and operational value for a networked system of high-performance, "weaponized" UAVs to effectively and affordably prosecute 21st century combat missions, including SEAD, surveillance, and precision strike within the emerging global command and control architecture.

The initial operational role for the J-UCAS desired for the Air Force is as a "first-day-of-the-war" force enabler that will complement a strike package by performing the Suppression of Enemy Air Defense (SEAD) mission through lethal and non-lethal means. In this role, J-UCAS would accomplish pre-emptive destruction and electronic suppression of sophisticated enemy integrated air defense systems (IADS) in support of manned strike packages. Throughout the rest of the campaign, J-UCAS would provide continuous vigilance with an immediate lethal strike capability to prosecute high value and time-critical targets. After the conflict, the J-UCAS could fly peacekeeping missions, such as enforcing "no-fly" zones; these missions typically entail flying long hours of patrols (so-called "dull" missions).

The initial operational role for the Navy's J-UCAS is to provide carrier-based, survivable, and persistent surveillance, reconnaissance, and targeting to complement manned assets and long-range precision strike weapons. But to fully exploit its potential and "buy its way" onto the carrier, SEAD and Strike capabilities will be incorporated into the design from the outset and fully developed in future spirals. The system will be seamlessly integrated with manned aircraft missions, carrier air traffic control, and deck operations, as well as with the carrier's Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance (C4ISR) architecture.

“Hard Problems” for the UAV Operator

UAVs currently require multiple operators to control a single UAV. J-UCAS requirements dictate a single operator controlling multiple vehicles. The operator must manage multiple “flights” (containing up to four UAVs in each flight) of vehicles. The tasks include target identification, weapons pairing, and attack. During this already complex task, the operator must also deal with vehicle system failures and logistic issues. All operations are conducted under critical time constraints that create high demands on cognitive processing capacity (Executive Function). Controlling multiple UAVs is cognitively demanding because of constant context shifting within and between tasks, which places a heavy demand for executive function and for each vehicle and between vehicles, a divided attention cognitive demand.

Transition Customer

The Boeing® team is working primarily with the U.S. Air Force as they are the initial transition customer for J-UCAS. The U.S. Navy is also interested in a carrier-capable version of the J-UCAS. The J-UCAS office, under DARPA leadership, with support from the services, is focused on planning and executing a demonstration program that supports Air Force and Navy future requirements. Operation Assessments (OAs) will follow the Demonstration program beginning in FY 2007. The OAs are expected to provide the services with several program options in FY 2007–2009. A Joint Requirements Group, composed of the Joint Staff, Air Force, and Navy, will coordinate with the Joint Forces Command and other combatant commanders to develop and validate J-UCAS requirements.

Test Conditions

The Boeing® prototype system is designed around the CSA. The CSA inputs biosensor data collected from a networked database and computes the Tactical Situation Display (TSD) and Vehicle Health Task (VHT) gauge values (cognitive load). The Augmentation Manager combines gauge data and context data to determine mitigation triggers based on a rule set. Mitigation initiation and termination is a joint function of gauge output and context in an “and” statement—they must agree. The computed CSA gauge values came from two different approaches during research and development. One approach was based on an ANN that received EEG, ECG, EOG, pupilometry, and fNIR sensor data. The ANN was used to detect the Attention and Executive Function bottlenecks. The other approach was based on a Statistical Process Control (SPC) model that received fNIR and pupillometry sensor data. The SPC model was used to detect the Sensory and Working Memory bottlenecks. The Integration architecture used for the Boeing® CVE is shown in Figure 6 on the next page.

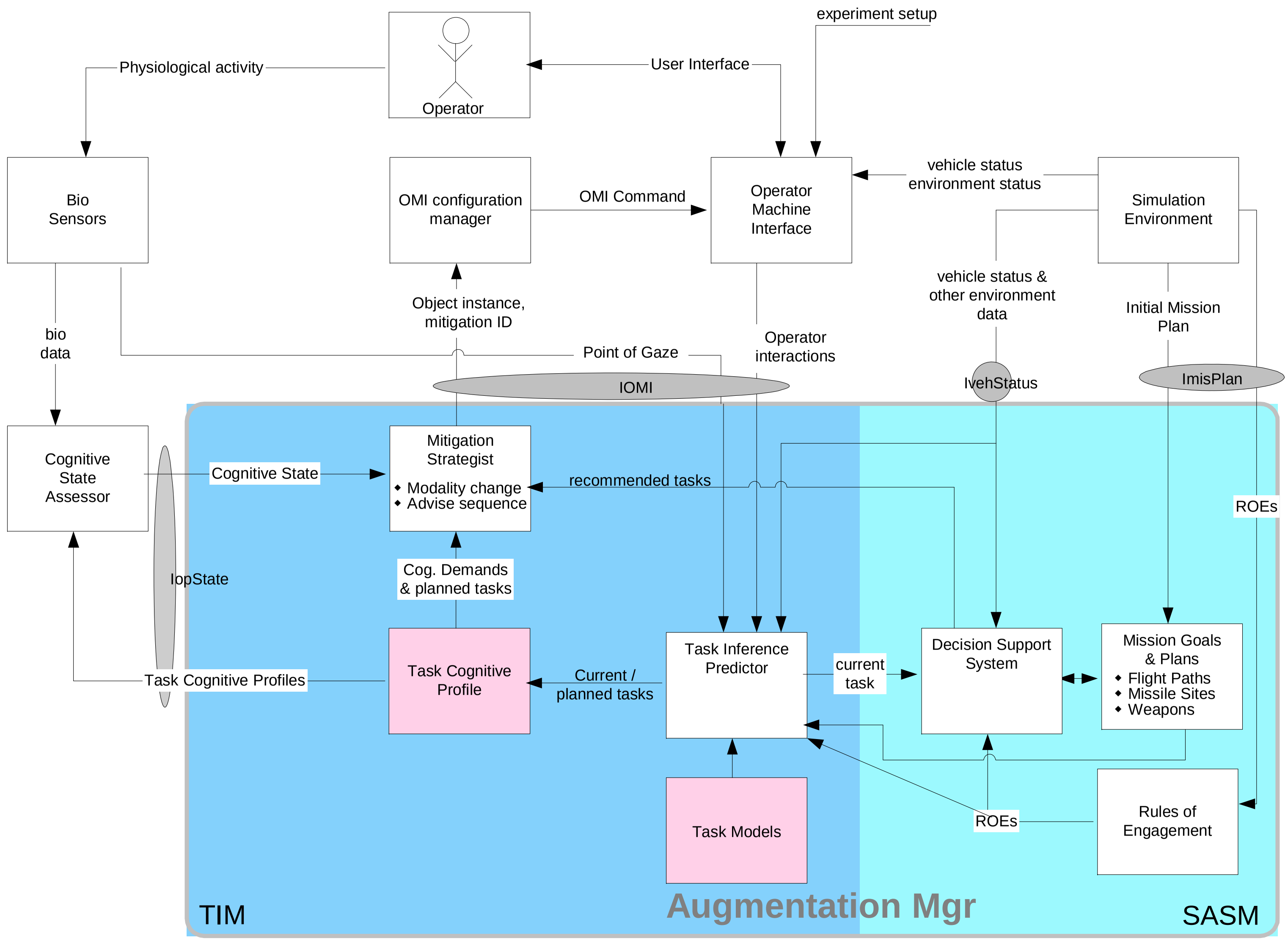

Figure 6. Boeing® integration architecture.

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2.4.4 Methodology

The test conditions for the Boeing® team consisted of a UAV operator console that housed two 19-inch flat-panel displays. The left display presented the TSD while the right displayed the targeting (Synthetic Aperture Radar [SAR] image and Designated Mean Point of Impact [DMPI] selection tool) and VHTs. For the Executive Function bottleneck, the operator, after finishing a VHT or performing a targeting task with the SAR image, had to switch tasks to the TSD. Once switching back to the TSD, the operator had to correctly pair the vehicle to target (12 vehicles to choose from) with the least amount of time remaining before overflight (or would miss the target).

Cognitive Bottleneck—Executive Function

The Executive Function (sometimes called the Supervisory Function) monitors and controls ongoing mental operations and actions. It selectively activates some memories and processes and inhibits irrelevant ones. Executive Function is critical to tactical decision-making that requires split-second assessment of the tactical situation. The assessment of the tactical situation can be easily lost, and the operator must be able to recover context quickly.

Mitigation

The Boeing® team based their mitigation strategies on cue memory retrieval to improve performance when Executive Function was overloaded. The goal was to maximize executive functioning and facilitate memory enhancement. The system used four mitigation techniques: Map De-clutter, Earcons, Book Marking, and Unified Book Marking. The details of these techniques are listed in Table 11 and in the Boeing® analysis report.

Cognitive Bottlenecks—Working Memory, Sensory Input, Attention

The Boeing® team also successfully researched mitigation techniques for the remaining three bottlenecks: Working Memory, Sensory Input, and Attention. The test conditions were the same as for the Executive Function bottleneck, with different task metrics.

Independent and Dependent Variables

The experiment used a competing tasks paradigm, within subject, 2 x 1 repeated measures. The independent variable was Mitigation ON or Mitigation OFF. The dependent variables were number of bombs on target (Executive Function), number of vehicle health tasks missed (Working Memory), number of events performed simultaneously (Sensory Input), and number of detected and engaged pop-up events, with versus without augmentation.

2.4.5 Results

The DARPA goal was to achieve a 100% improvement in the cognitive Executive Function bottleneck. The results obtained were statistically significant at the $p<0.5$ level, and were achieved within system performance constraints specified at the start of IWIIUS Phase II. As can be seen in Table 10, this goal was matched or surpassed for those bottlenecks addressed by the Boeing® team. For the Executive Function bottleneck (measured by number of successful bombs on target), a 241% improvement was observed, meaning that the operators' ability to strike assigned targets was increased nearly two and a half times when the mitigation techniques were implemented. Improvement results for Working Memory, Sensory Input, and Attention bottlenecks were 680%, 283%, and 750%, respectively.

2.4.6 Phase III Goals

Phase III will provide more challenges as IWIIUS technology is applied to increasingly refined J-UCAS operator environments. Challenges include the following:

- Under operational conditions of cognitive, physiological, and environmental stress, mitigate the impact of platform-specific stressors on cognition and information processing performance
- Developing multi-level gauges and augmentation management to increase system stability with high-performance mitigations
- Making the cognitive gauges and Augmentation Manager proactive rather than reactive
- Developing and testing gauges that are highly correlated with specific cognitive bottlenecks
- Incorporating context modeling and workload avoidance strategies
- Decreasing time for ANN training (currently takes too long and must be performed too often, perhaps every few hours)
- Increasing the redundancy of the sensors and gauges to increase the graceful degradation capability of the system
- Investigating wireless technology to increase the mobility of the operator
- Improving sensor fieldability (competition for space on the operator, ergonomics, ruggedization, etc.)
- Increasing operational fidelity of the system by expanding existing scenarios to include wider range of tactical problems and adding mission control station functionality
- Must clearly demonstrate 3-to-1 manpower reduction

A key area of research for Phase III and technology transition for Phase II and technology transition that warrants further investigation is architecting gauges that are an integration of multiple sensors (using ANN, SPC, or both). Gauges designed with this philosophy are expected to be more robust, and with a more graceful degradation response to failures than single-sensor systems.

Additionally, the development of an AugCog system could include methods for using part-tasks to baseline gauge readings for a given “task type.” That knowledge, along with knowledge of the operator’s current cognitive state, could be used to predict the occurrence of cognitive overload when starting the next task. This information could be used for a proactive workload avoidance approach in the design of the augmentation manager.

3. DISCUSSION

Humans are constrained in the amount of information they can manage at any given moment (Jiang and Kanwisher, 2003; Allport, 1993). DARPA, recognizing the operational implications of this problem for the military, has sponsored the Improving Warfighter Information Intake under Stress (IWIIUS) program. This program was developed to specially address methods for detecting and mitigating limitations of human information processing, and designing solutions to enhance the exchange and use of information in man–machine systems. This report is a compilation of the results of the second year, or Phase II, of the program. During this phase of the program, teams demonstrated how the effectiveness of warfighters can be improved by making the human–computer interface respond to specific human performance capabilities and limitations in stressful operational environments.

Phase II extended previous work by focusing on the development of closed-loop prototype systems that addressed theoretically derived cognitive bottlenecks. The closed-loop integrated prototypes (CLIPs), developed by each industry team, rely on computational systems to determine the state of the cognitive bottleneck in a warfighter in real time. Whenever the warfighter approached cognitive limits (minimum or maximum) of one or more of the cognitive bottlenecks, mitigation strategies were implemented, given the warfighter's current task requirements, to reallocate resources or redirect efforts of the warfighter to enhance overall performance. Optimizing the warfighter's cognitive state through these mitigation strategies reduced the limiting affects of the cognitive bottlenecks, thus maximizing information throughput of the warfighter. Each of the four teams investigated a different operationally relevant task specifically addressing one or more of the cognitive processing bottlenecks identified by the DARPA management team. The management team also established performance goals for each of the cognitive processing bottlenecks as criteria for success during Phase II.

With these goals in mind, the efforts of each team sought to demonstrate the *possibility* that closed-looped systems could be used to (1) enhance operational effectiveness through specific improvements to warfighter efficiency, (2) increase the amount of information operators can handle, (3) reduce manpower requirements (e.g., one person doing job of two or more), and (4) improve attention management during stressful operations. Each industry team provided detailed results (see Volume II). Their accomplishments are a significant step forward in the application of augmented systems within each of the operational environments investigated.

The Honeywell® team exceeded the objectives of Phase II by demonstrating that a closed-loop computational system can improve performance in a simulated dismounted-military environment (infantry). They showed that when appropriate mitigations were applied at appropriate times, significant improvement in attention could be obtained. Based on post-hoc analyses and comparison with critical events embedded in the test scenarios where high attentional demands were expected, the Attention bottleneck gauges appeared to accurately reflect high attention demands 98% of the time. The Honeywell® cognitive gauges could detect state changes within 250 to 300 ms of the onset of the critical events, and mitigations were invoked within 1 second of the critical event. These improvements are well within the system performance goals established for Phase II.

The success of the DCC team serves as the benchmark for performance improvement for military vehicle operators. Their results show a significant performance improvement on competing tasks when the closed-loop augmentation system was activated. Without the intervention, competing task performance was significantly lower during periods of high workload. The empirical results demonstrate improvements of 108% for the sensory–auditory bottleneck, exceeding the program goal

for the sensory bottleneck. A 72% improvement for the visual-sensory bottleneck was also achieved. This result is a significant improvement, especially considering that they were using real-world driving tasks on public roads. These tasks are highly demanding of sensory systems, leaving few resources available for competing visual tasks. A 103% improvement for working memory was shown over the baseline (non-mitigated) condition. Their results demonstrate that it is possible to detect cognitive states changes in real time and that this information can be used to provide a significant improvement in operator performance under closed-loop conditions in the real-world environment.

The long-range implications of the DCC augmented cognition technology in the LAV environment is twofold: First, the workload of the crew could be dynamically allocated between the driver, vehicle commander, and additional vehicle occupants by (1) better sharing of various tasks based upon the cognitive state of each crew member and the autonomous capabilities of the vehicle, (2) by using the augmented cognition system to focus the crew's attention on the most critical task, and (3) by having the augmented cognition system report on the cognitive status of crewmembers (during over- and under-workload conditions). Second, the driver's ability to safely operate the vehicle would be enhanced by (1) automating and assisting in driver functions when appropriate, and (2) prioritizing caution and warning indicators through the most effective sensory channel. These applications will be further explored in Phase III.

LMATL's neural network successfully classified working memory in the overloaded or under-loaded state over 90% of the time. The workload classifications took place in under 500 ms, and the mitigation was triggered 5 seconds from the time a working memory exceeded threshold. The results show a 642% improvement in working memory as measured by successful re-targeting performance when the intelligent sequencing mitigation was used. These results are operationally relevant to future TTWCS development since the added dimension of re-targetable Tomahawk missiles, in addition to the pressure for manning reduction, will dramatically increase the frequency with which TTWCS operators will experience working memory overload. LMATL identified several problems with current sensor systems, and plan to investigate the feasibility of using non-contact sensors during Phase III for an extended period in an operational environment. The LMATL's CLIP met all requirements for successfully addressing the Working Memory bottleneck.

The Boeing® team conducted a series of experiments, refining the bottleneck gauges and mitigation strategies iteratively based on empirical results throughout the development process. A subset of data obtained from these studies was used in assessing the bottleneck results. The Boeing® team met the performance goals for all the cognitive bottlenecks, demonstrating a 241% improvement for their assigned bottleneck of Executive Function. Cognitive state detections were successfully categorized into their appropriate state 92% of the time, within 1 second of its changing. Mitigations were implemented within 1 second of it being requested by the augmentation manager. These results exceeded the program goals of achieving a 100% improvement in executive function, with 90% or better accuracy in less than 2 seconds after a state change, and mitigating in less than 1 minute. The performance differences observed between the augmented and non-augmented conditions were statistically and operationally meaningful.

In addition to the general findings that operator performance could be improved using a variety of mitigation strategies, multiple lessons were learned, or additional problems highlighted, that have significant implications for the future of augmented cognition.

Lessons Learned. The combined efforts of each research team has addressed several important issues that needed to be identified, elaborated on, or resolved for the future development of operational AugCog systems.

The Need to Understand User. One fact that became relatively apparent is the need to conduct a Cognitive Task Analysis (CTA) to fully understand the decision-making required in the performance of operational tasks. Having a clear understanding of who the user is as well as thoroughly understanding what it is about their job that is cognitively difficult, is crucial to developing meaningful and effective AugCog systems. There appeared to be a direct correlation between the quality and depth of the cognitive task analyses conducted at the start of Phase II, the ease with which the CLIP was developed, and the ultimate success the development teams had in demonstrating an effective CLIP. One team (Boeing®) had difficulty defining the context with which the warfighter operated (largely because the role of the warfighter in this environment is still ill-defined). For another team (LMATL), application focus changed (from Aegis to Tomahawk) mid-way through Phase II development, which meant that much of the thinking about the hard cognitive problems done earlier had limited applicability to their final CLIP. Several teams had difficulty distinguishing between a traditional task analysis, which focuses more on what the operator is doing, and cognitive task analysis, which focuses more on the decisions made and thought processes required to complete the task. Current research efforts had limited opportunity to investigate specific characteristics that a military user is often exposed to that can affect operational performance, such as fatigue, periodic changes in cognitive demand, and conflicting demands for attention, etc.

These findings support the notion that a cognitive task analysis should be conducted to fully understand the decision-making requirements of the operational performer. Having a clear understanding of who the user is, as well as thoroughly understanding what they do is essential for successfully constructing future AugCog technologies.

Integrate Early—Integrate Often. During the course of Phase II, addressing the integration of the various sensors, computer hardware, and software early in the development cycle paid off for developers that could do it. The earlier and more thoroughly the integration was considered, the fewer the setbacks and more effective the mitigations. Slight modifications in sensors should not be treated superficially, and require systematic assessment throughout development.

Development Strategy. A project execution model that entails continuous (incremental) experimentation was the best approach in meeting the larger project objectives, rather than developing around less frequent and more sophisticated integration exercises. However, there is often some cost in terms of scientific and experimental rigor in this approach. Perhaps the best balance is a mix of execution strategies where a distinction is made between developmental experimentation and formal empirical testing. Teams that were highly successful conducted step-wise assessments identifying the contributions to each individual modification.

One Sensor Gauge Does Not Fit All. It has been interesting to observe how the sensors and cognitive state gauges developed during Phase I of this program have been applied over the course of Phase II. Some gauges that were thought to be the most robust during Phase I have been found to be less effective and/or useful when they were applied to the various operational requirements while other gauges that were considered “marginal” during the Phase I TIE have provided very effective results and operational utility. Gauges that seemed to work well for one of the teams in their application, sometimes worked poorly for other teams within their application. In other words, the selection of specific gauges for use within the operational environment is highly context (task)-dependent.

Some performers are still struggling with the development of specific cognitive state gauges and some continued to revise and develop their gauges—which were constantly changed to meet the demands of the operational tasks. This approach directed a great deal of effort and resources for some teams away from the core goal of developing meaningful and compelling illustrations of AugCog into basic research to better identify a sensitive gauge. It may be that cognitive gauges that demonstrate some utility in simulated tasks lose their direct applicability as tasks become more cognitively demanding. Teams that ignored the theoretical constructs of the gauges developed in Phase I and focused their efforts on integrating their collection of gauges through a neural-network (or equivalent) algorithm, demonstrated enhanced performance. A major problem with using this approach is that it is unclear what specific aspect of cognitive activity was used to trigger the augmentation strategy. In several cases, it was unclear whether the performance enhancement was caused by appropriately implementing an intervention strategy to augment cognitive performance or simply caused by using advanced automation or improved HCI. Clearly, the basic science of Augmented Cognition is still in its infancy and the specific application of cognitive state gauges will require significant future investment.

Cognitive Bottlenecks May Be Task-Specific. The notion of isolated cognitive bottlenecks has significant appeal for a theoretical standpoint; however, it appears that when applying these concepts to real-world tasks, they are often overlapping or interacting. It remains to be seen if (1) we have not adequately defined what we mean by cognitive bottlenecks and our current understanding simply lacks sufficient specificity to be useful, or (2) if the concept of "cognitive bottlenecks" even has practical utility in developing AugCog systems. We may have to rethink the whole notion of cognitive bottlenecks and define them operationally in terms of the specific demands of decision-making tasks for a given application. In other words, the operational definitions and the theoretical definitions do not seem to directly correspond. It might be more useful to define bottlenecks and gauges in terms of the tasks that are to be mitigated vice attempting to address conceptual bottlenecks. However, regardless the operational definition of a specific bottleneck, the net result of the mitigation strategy improved overall task performance.

Artifact detection. Phase II was one of the first serious attempts to study what up to now have been largely laboratory phenomena in an applied military operational setting. Before IWIIUS, experimental tasks tended to be very simple, highly controlled laboratory experiments.

The objective of the basic research accomplished during Phase I was to identify underlying physiological phenomena that correlated to specific cognitive behaviors. Phase I culminated with the premise that there were now known physiological phenomena that could be reliably associated with cognitive activity and, therefore, real-time or near-real-time gauges could now be constructed to detect these phenomena in more complex analogs of operational tasks. Phase II enhanced these "gauge" technologies and applied them to more operationally meaningful laboratory and field-test settings. As realism of the task has increased, so has the need for advanced processing to rapidly detect the physiological phenomena of interest as well as remove those unwanted physiological artifacts from the raw data that would prevent the AugCog systems from detecting the appropriate cognitive state of the operator.

One concern of artifact detection that was highlighted in Phase II and is identified as an urgent concern for the future advancement of the science of augmented cognition is the ability to decipher between physiological changes related to cognitive activity vice the physical requirements of the task. This subject was of vital concern of the teams addressing operations in a moving vehicle (MEFFV) or for the dismounted soldier (FFW) that have already run into issues with the impact of physical (muscular) activity on the ability to detect cognitive phenomena. Both development teams see a critical need in addressing this issue during the next phase of development.

Perceived Stability/Trust. Another significant issue critical for the advancement of AugCog is to not only accurately identify when a decline in cognitive performance occurs, but to also initiate an appropriate mitigation to enhance performance in a predictable manner. Looking across the current development efforts, the triggers used to initiate most mitigations are typically not the same trigger used to turn the mitigations off. The issue with stability and predictability of the mitigations is further complicated by a combination of physiologically based gauges in conjunction with context-based sensors. If the operator did not understand the logic, the rationale for triggering the onset/offset of the mitigation, the potential for disruption and degraded performance is significant. The more complex the mitigations and potential triggers, the greater the problem with them being perceived as predictable and ultimately useful.

Another dimension of system stability that relates to the impact of degraded sensors is that each of the teams indicated that while their systems would continue to offer some degree of augmentation with the loss of one or more cognitive state sensors, the functionality of their systems would change. If users are not aware of the degraded functionality of the system, their expectations of augmentation would not be met, and the system might be perceived as unstable. Before such a system is deployed, the issue of training will need to be developed to allow users to operate in the face of degraded augmentation (familiarization with system capability and limitations).

Timing. Many of the changes in perceived cognitive load may be momentary, occurring only for a brief time. The physiological measures used as gauges for the industry teams may detect a transient or sustained change in cognitive activity. For instance, a P300 event is a transient measure that typically occurs upon the recognition of a significant event. Its magnitude has been used as a measure of surprise or cognitive workload.

However, the P300 occurs briefly and is typically useful only in detecting the start of an event. A different measure must be used to detect low workload.

It may be unrealistic—or at least have little practical application to have a system that is sensitive enough to detect and implement mitigation in terms of seconds. It is clear that in the operational environment, momentary changes in one or more of the cognitive bottlenecks areas may occur fairly rapidly (<1 minute). Research needs to be conducted to investigate optimal timing for implementing various mitigation strategies.

Hardware Integration. Note that the time to set up the sensor suite for all four teams was on the order of 1 hour per test session/participant. Gauges and/or neural networks required significant time and effort for calibration during each test session, taking 10 to 45 minutes for each test run, and in some cases, for each of several gauges. Experimentation with reusing calibrations across participants, or even for the same participant across multiple runs, was limited; however, the results found by the four development teams suggest that the underlying phenomena that the gauges are based on, as well as the artifacts that must be removed for reliable gauge performance, will require that fielded systems be calibrated before each use. Efforts must be expended to streamline the calibrations process and make it feasible under field conditions.

The sensors used during Phase II are still physically independent. All four teams noted that a significant technical objective for Phase III of the IWIIUS program must be to physically integrate the bio-medical sensors with the objective of making them more robust, easily donned, and readily calibrated. Placement of electrodes and the quality of their physical contact with the user remain problematic. The teams are, or anticipate, using some wireless sensor systems during Phase III; however, these systems will present their own integration issues, which have not yet been addressed adequately for field testing.

Electrical interference remains a significant issue, though it was effectively addressed by most teams through trial and error throughout development. Phase III will require that significant consideration be given to potential interference sources in the field, and then anticipating design solutions that avoid the issue in the first place. Again, integrated sensors designed for use in the field from the outset, vice adapted from laboratory or medical applications, are likely to address this issue adequately.

Context Gauges. Most development within the IWIIUS program has focused on cognitive state gauges. It is becoming quite clear that these are necessary, but not sufficient, for effective AugCog systems. Each team cited the requirement for what might be called "context gauges," that is, algorithms and sensors that would allow the augmentation system to have inputs regarding what is happening in the environment of the augmented user. Such inputs will be critical in determining which of several mitigations might be applied, as well as when it is appropriate to turn the mitigation off; however, these gauges were not explicitly developed as a current part of the IWIIUS program.

Individual Differences. The development teams reported significant issues with inter-individual and intra-individual differences, particularly for the EEG-derived gauges. The frequency bands of interest were very low (on the order of 4 to 20 Hz), and variation from participant to participant was significant. The teams using techniques other than neural networks found that the phenomena of interest occurred outside the preset band filters for approximately one in five participants. The teams that tried to use generalized filters or inadvertently used filters that had been trained for other participants consistently got poorer results for EEG-derived phenomena.

Another aspect of the underlying EEG phenomena that is poorly understood is the effect of extensive experience with the tasks on the utility of EEG derived gauges. It appears that successful utilization of EEG data in a AugCog system will require that the filters used in separating signals from artifacts must be tailored to every user.

A related aspect of this issue that must be further investigated is the apparent drift in the frequency bands for the phenomena of interest. It was observed on an anecdotal basis that after a session of as little as 40 minutes and up to 3 hours, that the bands appeared to shift and the filters/neural networks might need to be reset. It is not clear why this shift occurs, and has not been previously reported in the literature. Again, this suggests significant additional work may be required in filtering the artifacts associated with neurological phenomena, and that they may have to adapt dynamically while an AugCog system is used.

Proactive vice Reactive Augmented Cognition. The current systems developed are largely reactive in that the user must first become overloaded, or at least close to overloaded, before the system will introduce one of the mitigations. Although it is important to detect when such levels of activity occur, it would be of great operational importance to develop a metric to be predictive (proactive) rather than reactive.

Metrics. The assessment of a AugCog system still remains problematic. All four of the development teams had difficulty wrestling with the appropriate level of analysis for assessing the impact of their system. The difficulty stems from whether we are trying to assess the effectiveness of detecting changes in the cognitive bottleneck gauges, the effectiveness of the mitigations, or the effectiveness of the overall human–machine system in performing some task. The focus of Phase II was on demonstrating the ability to assess and mitigate bottlenecks. As the IWIIUS program moves to Phase III, the human–machine level of analysis will be of greatest interest to transition sponsors and the most important level of analysis. The definition and use of appropriate metrics for AugCog systems will still continue to be an important issue as the program moves into Phase III.

Conclusion. Phase II of the IWIIUS program was an unqualified success. All four of the conceptual bottlenecks identified at the start of Phase II were successfully addressed by one or more of the development teams in four different military application environments. Each team demonstrated the ability to detect high cognitive load within a specific bottleneck by using physiological measures of cognitive state. These measures were then used as a trigger to initiate an appropriate mitigation strategy at the appropriate time, providing significant improvements in operator performance. The magnitude of the performance enhancements varied, depending on the task environment and bottleneck. Performance enhancements well in excess of the DARPA goals established at the start of Phase II were realized. The IWIIUS program continues on track, and teams continue to extend their efforts from the laboratory to the real operational environment under stress during Phase III of the program.

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This report documents the successful completion of Phase II of the Defense Advanced Research Projects Agency (DARPA) Improving Warfighter Information Intake Under Stress (IWIIUS) program. It describes the successful results of four industry teams building Closed-Loop Integrated Prototype (CLIP) systems that demonstrate how the limitations of human cognition can be addressed by augmenting cognition with advanced cognitive state sensors that provide input to complex computational systems. A cognitive bottleneck was identified by each of the four development teams along with empirically testable goals. The bottlenecks were operationally defined in terms of the application environments addressed by each of the four teams.

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